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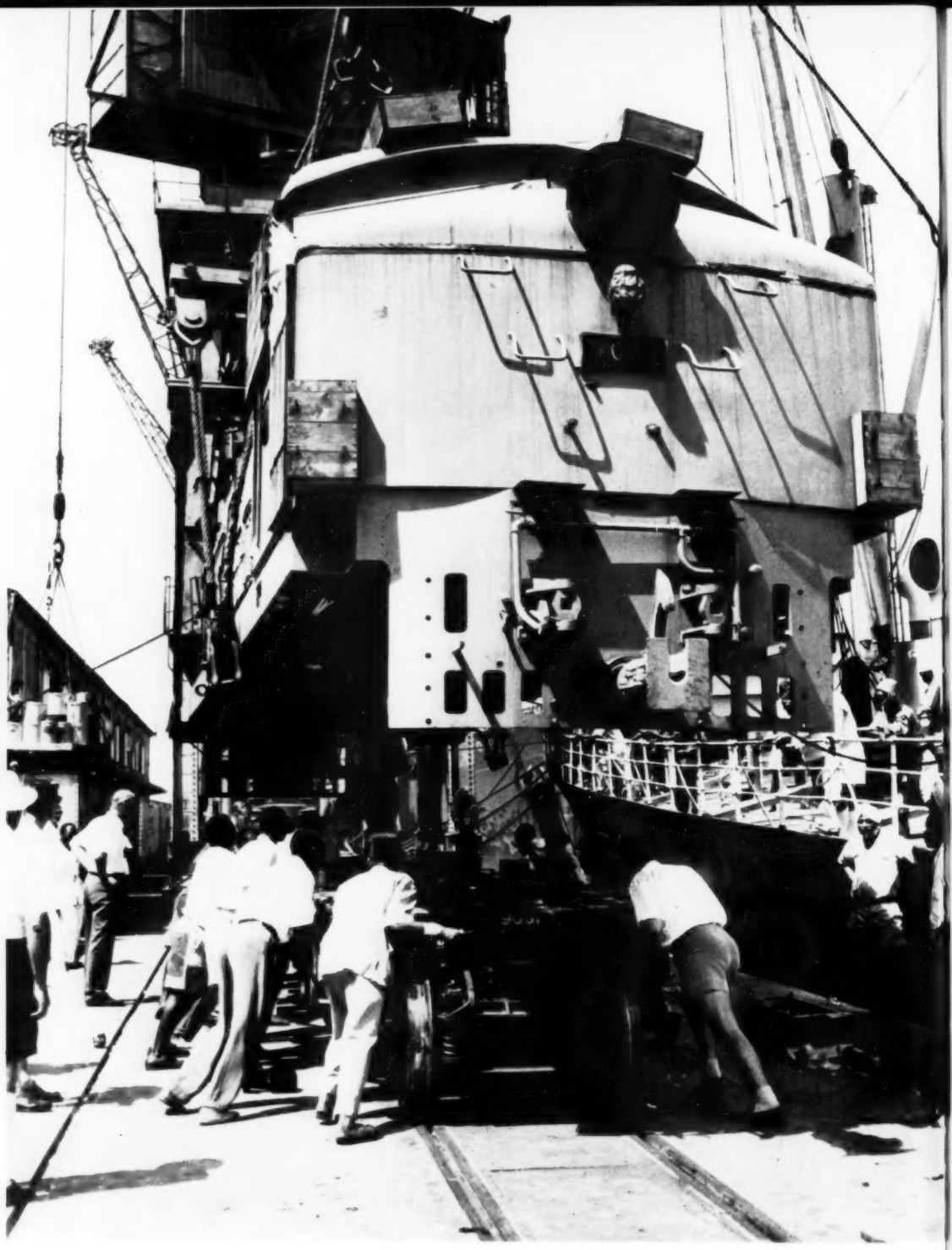


OFF-LOADING AT MOMBASA. *An 'English Electric' 1,840 h.p. diesel-electric locomotive being lowered on to bogies on arrival at Mombasa, for service with the East African Railways and Harbours Administration. Ten of these locomotives, which have 1-Co-Co-1 wheel arrangement, have been shipped for operation on the Nairobi-Nakuru route.*

The Uses of Waste Heat from Diesel and Dual Fuel Engines

by N. D. WHITEHOUSE, M.Sc., A.M.I.Mech. E., Chief Research Engineer, Diesel Engine Division, and A. STOTTER, M.Sc., Dipl-Ing., Senior Research Engineer, Diesel Engine Division.

This article is in all essentials a reproduction of the paper presented at The World Power Conference held in Madrid, 9th June, 1960.

DESPITE THE INCREASING utilisation of water power, nuclear power and others, fossil fuels such as coal and oil are likely to remain the main sources of energy for many years. The pessimistic prophecies of the exhaustion of these fuels, particularly of oil, on which modern civilisation is so dependent, are still far from fulfilment. Nevertheless these fuels are wasting assets, and need to be conserved. The continual increase in energy requirements throughout the world also emphasises the need to utilise all that is available as efficiently as possible.

The diesel engine is accepted today as one of the most efficient means of converting heat into work but it must be admitted that this efficiency is relative rather than absolute. An efficiency of from 30% to 40% is normally regarded as satisfactory. In other fields of human activity a wastage of 60% to 70% would not be regarded with equanimity.

Further improvement in the efficiency of the diesel engine may not be negligible but it is certainly limited. The simple and practical solution is to convert the waste heat into a useful by-product. Fortunately the waste heat from the diesel engine is of a sufficiently high grade to be valuable for many purposes, although not at such a high energy level as to be very suitable for the direct generation of mechanical power in any quantity. Installations where 75% to 85% of the available energy in the fuel is effectively utilised are becoming quite common.

Some of the many methods by which this waste heat may be used are dealt with here, giving a brief mention to the common form of space heating and hot water supplies which have been publicised extensively in many papers, but devoting rather more space to other applications such as refrigeration and water distillation.

Quantity of Waste Heat Available

The amount of waste heat recoverable from a diesel or dual fuel engine varies according to its type, the design of the engine and the load. The major part of the waste heat is rejected in the exhaust gases, usually about one-third of the heat available in the fuel consumed, and a further large quantity, say about one-fifth, is rejected to the engine-cooling water.

It is not the intention here to deal at length with the various ways in which waste heat may be converted into useful heat, or the ways in which the proportion of the heat used may vary. This has been covered before, and references are listed in a bibliography at the end of this paper.

In general the waste heat may be converted into hot water or into steam, or both, as desired for any particular installation. The percentage of the heat that can be made available may be increased slightly as the temperature at which it is required is lowered, but usually all of the cooling-water heat may be utilized, and a part of the exhaust heat, leaving the exhaust gases to be rejected at about 350°F.

Fig. 1 illustrates the quantities of heat available on this basis in three forms, either naturally aspirated, supercharged or supercharged and after-cooled.

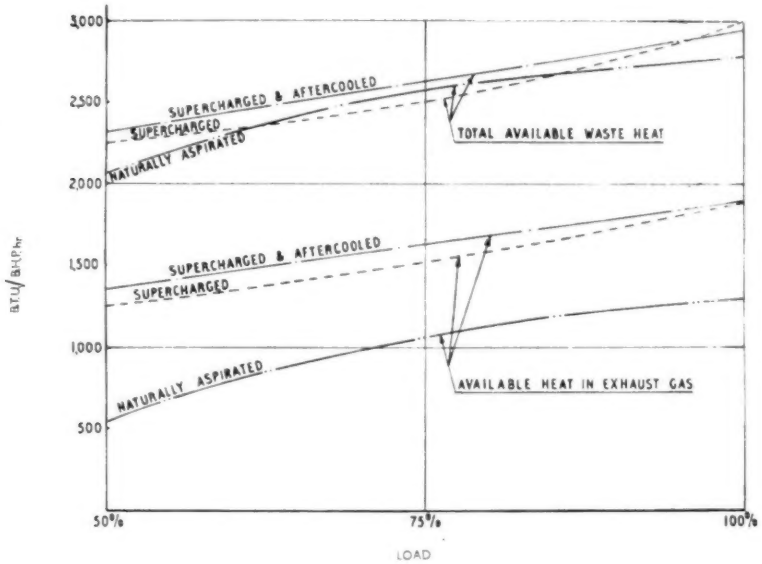


Fig. 1.—Available heat from naturally aspirated, supercharged and supercharged aftercooled engines

These three categories may be described as follows :

A naturally aspirated engine takes in air at atmospheric pressure and is correspondingly rated to give a low output ; a supercharged engine uses an air compressor to increase the pressure and density of the air to the engine, so increasing the amount of air available for combustion and hence the output ; a supercharged-aftercooled engine both compresses and then cools the air to obtain

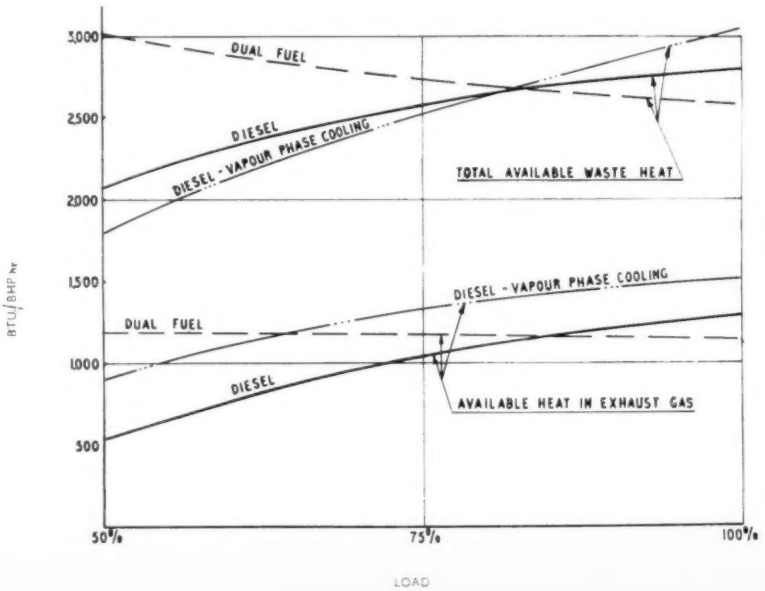


Fig. 2.—Available heat from diesel, dual fuel and vapour phase cooled engines

even greater air density. In the cases under consideration the supercharging is achieved by an exhaust gas turbo-charger, which utilizes part of the exhaust gas energy to drive the air compressor. This is the usual supercharging method with four-stroke cycle engines.

It may be noted that the heat available, as a percentage of the power output, is almost the same for any of these three engine types, but the supercharged engine has more available from the rather higher grade source, the exhaust gases, than has the naturally aspirated engine.

If all of the available waste heat is required as steam the jacket water temperature may be increased, the system pressurised and the heat to water can be rejected as steam at say, 10 to 15 p.s.i. gauge pressure. This method of cooling the engine, known as vapour phase cooling, reduces the heat to water, especially at low loads, and tends to increase the heat to exhaust. It also increases general engine temperatures, which may be beneficial or adverse depending upon engine loading, rating, design and type of lubricating oil used. Many such installations have been operating satisfactorily for years and it may now be regarded as established practice.

Fig. 2 illustrates, for a naturally aspirated engine, that the amount of heat available from an engine with such high temperature cooling is not very different from that obtainable with more conventional water cooling. A further curve on this figure is given to illustrate the heat available from the same engine, which was a dual fuel engine, when conventionally cooled and running on sludge gas. In this case the available heat did not fall off quite so rapidly with load decrease as when running on fuel oil alone.

The dual fuel engine is essentially a diesel engine, adapted to run on gaseous fuel with oil injection for ignition purposes, which can also be changed over to operate on oil fuel only. To obtain maximum part-load efficiency when on gas it is desirable to restrict the air supply to the engine, maintaining a gas/air ratio which gives satisfactory combustion. This procedure automatically maintains a high exhaust gas temperature and thus increases the available heat.

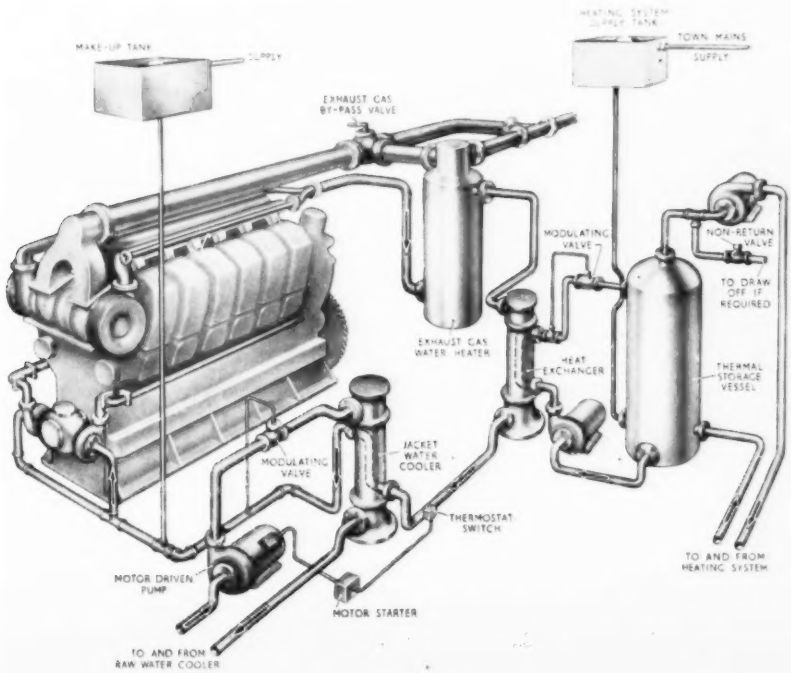


Fig. 3.—A typical diesel waste heat utilisation plant

Space Heating and hot Water Supplies

The most obvious application of waste heat such as that obtained from a diesel engine, particularly in a cold climate, is to heat buildings and provide hot water supplies. This is now a common practice and numerous stores, factories and offices exist where this is done.

The type of waste heat recovery circuit may be varied considerably to suit special requirements. A typical waste heat recovery plant is shown in Fig. 3. This is suitable where large quantities of hot water are required for space heating or hot water supplies. The waste heat may also be obtained as steam, or as part steam and part hot water if required.

It is not the intention in this paper to deal exhaustively with the numerous variations possible with these circuits or the particular engineering requirements. These have been dealt with in many earlier papers, given in the bibliography.

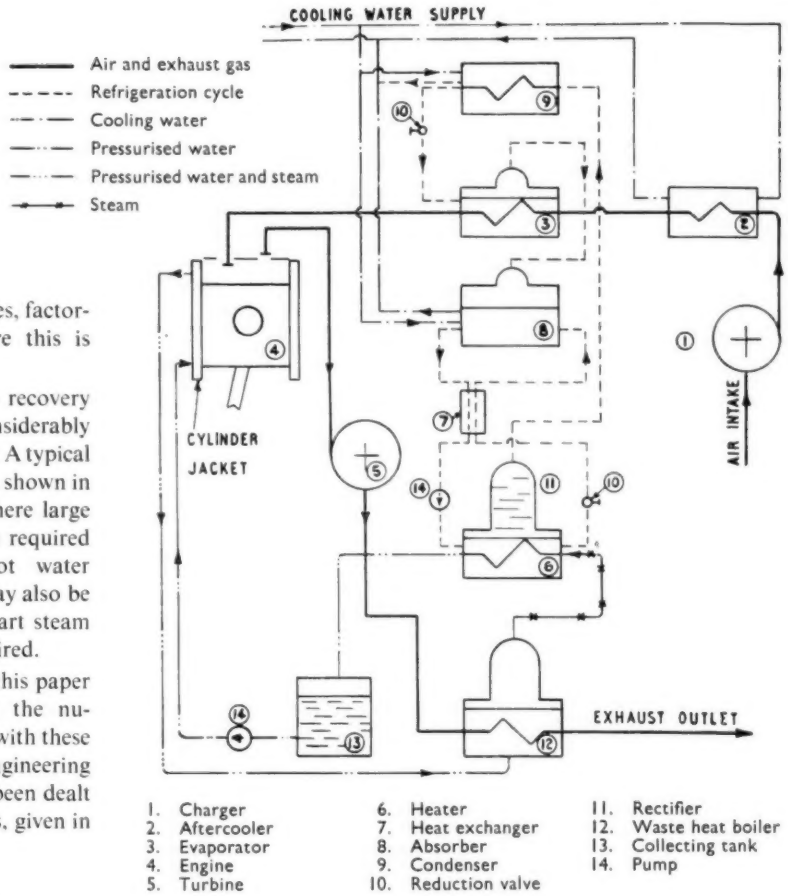


Fig. 4.—Schematic diagram of an installation using engine waste heat for refrigeration purposes

Absorption Refrigeration

In the following section the possibility of an absorption refrigeration plant driven by waste heat will be examined from two different aspects:

(i) Diesel charge air cooling for engine uprating.
(ii) Production of 'cold' for commercial cooling and air-conditioning purposes.

Since such a combination is attractive, particularly in hot climates, it is of interest to investigate the functioning of such a plant under different climatic conditions and different facilities for heat rejection.

Diesel Charge-Air Cooling by Refrigeration

British Standard 649 : 1958 on Diesel Engines for General Purposes gives de-rating formulae for changes in ambient conditions, such as that a supercharged diesel engine should be de-rated by 3% for every 10°F. increase of the ambient temperature above 85°F., and a supercharged aftercooled engine should be de-rated by 3% for every 10°F. increase in aftercooler water temperature above 75°F. These figures indicate the importance of air inlet temperature on the output of a diesel engine, and suggest that a considerable increase in power output could be achieved by refrigerating the air after the turbocharger instead of merely cooling it.

One method, which has been discussed in some detail in a paper delivered to the C.I.M.A.C.

conference at Wiesbaden in June, 1958, was to use a mechanically driven refrigerator after the normal supercharger and aftercooler, to cool the intake air to 40°F. This proposal gives the possibility of a considerable uprating, despite the power required for the refrigerator, but specific fuel consumption is worsened.

The use of an absorption type refrigerator has also been examined, and if driven by waste heat this would avoid the parasitic power losses of the mechanically driven refrigerator. In Fig. 4 a schematic diagram of such an installation is given. In this investigation an ammonia-water cycle has been considered, using the diagram by Merkel and Bosnjakovic for the cycle calculations, but the conclusions will not differ considerably for other media using the same thermodynamic principles. The refrigerator is a single-stage absorption unit including a heat exchanger and rectifier ; (details of the design and operation of such plants is beyond the scope of this paper). The steam is generated in the diesel engine cooling jacket and in a waste heat boiler heated by the exhaust gases, and supplied to the heater of the refrigerator unit. With this arrangement further up-rating and better fuel consumption are obtained.

Unfortunately these advantages are reduced or nullified, with conventional equipment so far examined, by the cost and weight of the refrigerating plant. This is particularly so for small and/or mobile installations. However, the quantity of waste heat utilised for charge-air refrigeration is usually a small percentage of the total, and as charge refrigeration is required only when the engine is on very high load, the possibility of utilizing charge air refrigeration with other refrigerating and air-conditioning requirements is attractive, particularly for tropical conditions. Some estimates of cost savings are given in the Appendix.

The effect of charge refrigeration on the power output of a particular supercharged aftercooled engine is shown in Table I.

Comparison is made between the power output under standard conditions, that is air temperature 85°F., aftercooler water temperature 75°F.; tropical conditions, with 100°F. air temperature and 120°F. cooling water for the aftercooler, as may be obtained with radiator cooling ; and refrigerated conditions where the air from the aftercooler is further cooled to 45°F.

While the British Standard method of de-rating is a sound guide for the purpose for which it was prepared, it would not be sound practice to use it in reverse for up-rating purposes. Fortunately, modern digital computers make possible a more detailed analysis of the effect of changes, such as ambient temperature, on the engine than would be practicable without them. The necessary methods have been programmed for DEUCE (Digital Electronic Universal Computing Engine) and have been used to compile Table I, which gives the results obtained for a supercharged aftercooled engine, the same engine which has provided the experimental data referred to earlier. The methods of calculation used have thus been checked by experimental results.

TABLE I

COMPARATIVE PERFORMANCE FIGURES : SUPERCHARGED DIESEL ENGINE WITH AFTERCOOLING

CASE	(i)	(ii)	(iii)
Description	Standard	Tropical	Refrigerated
Air temperature F. ..	85	100	—
Aftercooler water temperature F.	75	120	—
Charging air pressure temperature in. Hg. gauge	14·3	14·3	14·3
Air manifold temperature F.	95	135	45
Engine b.h.p.	566	518	620
Air flow through engine lb/b.h.p./hr	13·5	13·4	13·6
Exhaust temperature after exhaust turbine F.	840	867	803
Power output as % of standard	100	91·5	109·5
Specific fuel consumption lb/b.h.p./hr	0·380	0·384	0·379
Trapped air/fuel ratio ..	23·6	24·0	23·6
Heat losses B.t.u./cycle	7·1	7·1	6·8
Peak cylinder pressure p.s.i.	970	970	970

The terms (i)-(iii) in Table I are the criteria which have been taken to be the limitations on maximum output for this engine. That is, it is considered that the cylinder pressure should not exceed 970 p.s.i. ; the heat losses, which are an indication of

thermal loading, should not be more than 7·1 B.t.u./cycle ; and the mass of air available for combustion should be no less than 23·6 times the mass of fuel to be burnt. A fourth limitation could have been on exhaust temperature, which would have resulted in a further de-rating for tropical conditions to something near the British Standard de-rating of 3% per 10° F. on cooling water temperature above 75° F. It may be seen that the limitation in the case of an engine with intake air cooled to 45° F. is not the same as that with an engine operating under the adverse tropical conditions noted. There is no simple rule determining the power output obtainable under different conditions ; this would vary from engine to engine ; but while application of the B.S. de-rating formula is conservative for tropical conditions, to reverse the formula for refrigerated conditions could result in an excessive up-rating.

Application of Refrigeration

Two applications have been considered below, A and B in Table II. In one case the temperature of the coolant has been assumed to be 32° F., suitable for a cold store, and also for cooling the charge air of the diesel engine to a temperature of about 45° F. These temperatures have been taken to ensure that there is no danger of icing of the evaporator on the air side, as this would restrict the air supply to the engine.

In the second case the refrigerator operates at the common coolant temperature for air-conditioning purposes ; a coolant temperature of 54° F has been taken to give an air temperature of about 67° F.

The efficiency of the refrigerator depends on the temperatures in the evaporator, condenser and heater, and the overall efficiency is thus largely dependent upon the application and the climate and geographic conditions.

The following possibilities have been examined :

STANDARD CONDITIONS

(i) Ambient temperature 85° F. Cooling water 75° F.

TROPICAL CONDITIONS

(ii) Ambient temperature 100° F. Cooling water 120° F., assuming radiator cooling.

(iii) Sea or river cooling water at 85° F.

TABLE II

REFRIGERATOR CAPACITY AVAILABLE FOR DIFFERENT CONDITIONS

CASE	(i)A		(i)B		(ii)A		(ii)B		(iii)A		(iii)B	
Ambient temperature (° F)	85	85	85	85	100	100	100	100	100	100	100	100
Cooling water temperature (° F) ..	75	75	75	75	85	85	85	85	120	120	120	120
Engine output (%)	100	75	100	75	100	75	100	75	100	75	100	75
Steam temperature (° F)	244	244	244	244	244	244	244	244	286	286	244	244
Available waste heat to steam (Btu/b.h.p./hr)	2850	2620	2850	2620	2850	2620	2850	2620	1780	1620	2850	2620
Cooled air temperature (° F) ..	45	45	67	67	45	45	67	67	45	45	67	67
Efficiency of refrigerator	·600	·600	·690	·690	·540	·540	·660	·660	·360	·360	·530	·530
Total production of 'cold' (ton/b.h.p./hr)	·149	·137	·164	·151	·137	·126	·156	·144	·064	·058	·138	·129
Quantity of 'cold' used for diesel air cooling	·023	·020	·011	·009	·030	·028	·016	·014	·068	·063	·034	·031
Available cold for air-conditioning or cold storage	·126	·118	·153	·143	·107	·102	·140	·134	—	—	·104	·098

A Refers to coolant temperatures of 32 F. B Refers to coolant temperatures of 54 F.

The heating temperature may be critical when the lower coolant temperature is required. Two possibilities have been considered, one with steam generated at 12 p.s.i. gauge, 244°F., which is suitable for vapour-phase cooling and exhaust boiler steam generation and will cover the requirements for air-conditioning under all ambient temperatures considered. It is also suitable for the cold-store application under standard conditions, and under tropical conditions with sea or river cooling available. For tropical conditions with less favourable cooling, as with radiators, the refrigeration cycle would be inefficient, giving very little cooling, and utilization of the exhaust heat only is considered, with steam generation at 44 p.s.i. gauge, 286°F. temperature, and ammonia vapour temperature in the heater of 275°F.

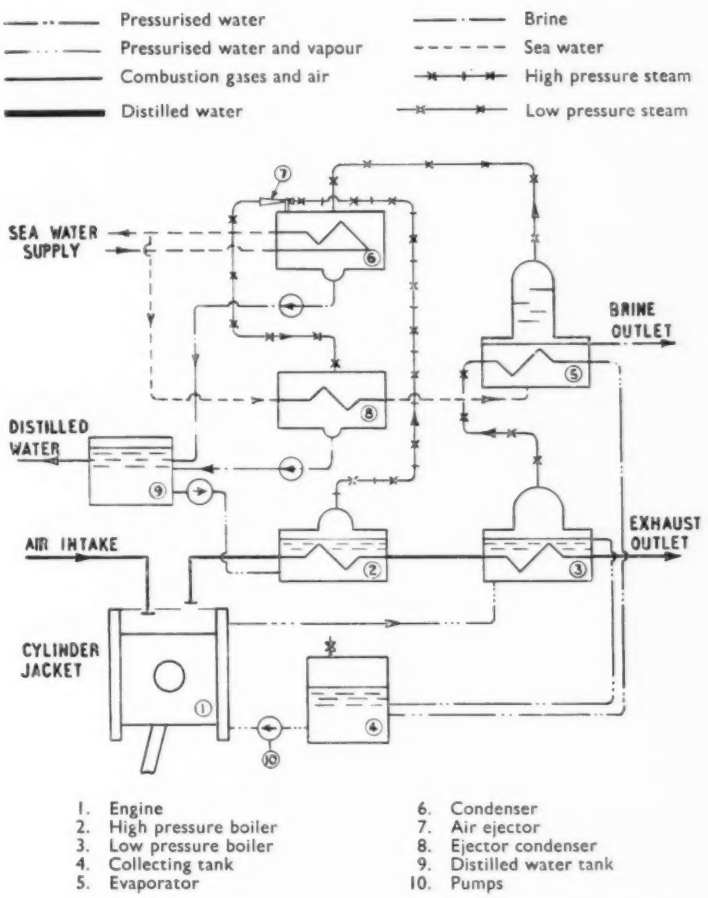


Fig. 5.—Schematic diagram of an installation using engine waste heat for water distillation purposes

The quantities of heat and 'cold' available under different conditions are shown in Table II, with the assumption that charge refrigeration is used throughout. If charge refrigeration is not used the total production of 'cold' is available for air conditioning or cold storage. The advantages of either method would need to be compared for any particular installation, to suit the site requirements. There are numerous possible combinations to be considered. Thus up-rating by air-charge refrigeration might be worth while in one case where it resulted in a reduction in the total number of engines required, but not in another where the increase in power was insufficient to reduce the number of engines installed.

It may be noted from the above table that full charge refrigeration to 45°F under conditions of high ambient and high cooling water temperature is not practicable. It would certainly not be economic.

The De-salination of Sea Water

Whenever a diesel engine is installed near salt water in regions where there is a lack of pure water the waste heat may be used to produce distilled water. Typical examples of conditions where this combination may occur are marine installations, off-shore oil drilling and military installations in deserts bordering salt water supplies.

1. Dual fuel engine
2. Exhaust heater
3. Digester water heater
4. Digester water cooler
5. Digester
6. Oil cooler
7. Air cooler
8. Pumps
9. Gas compressor
10. Thermostatic valves

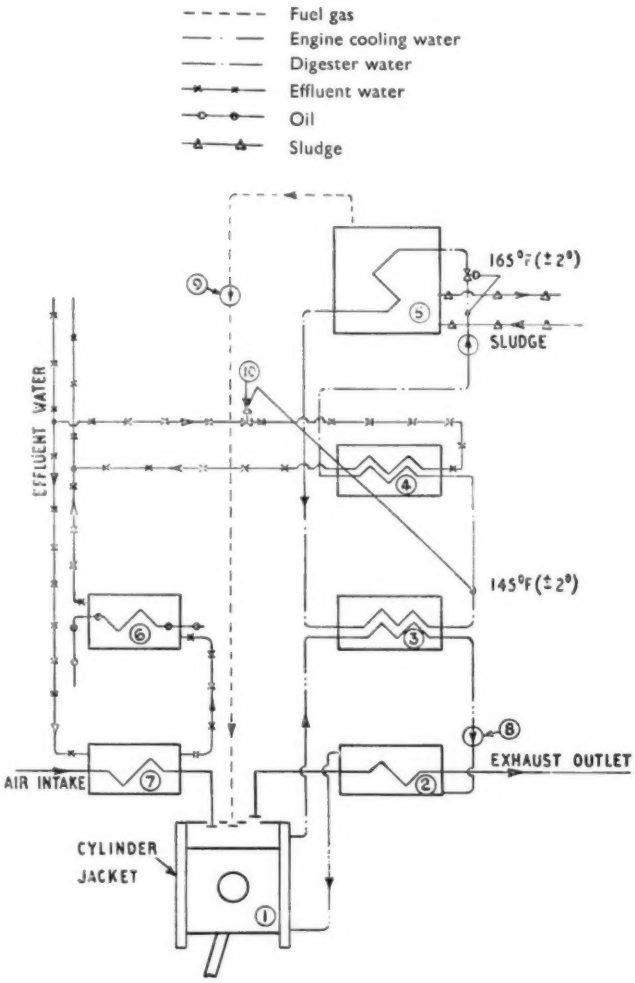


Fig. 6.—Schematic diagram of an installation using engine waste heat for fuel gas production from sewage sludge

The de-salination of salt water requires considerable quantities of heat for small return. It is therefore not economic where the heat is expensive, but may be ideal where waste heat is available and small quantities of pure water are required.

In Fig. 5 a schematic diagram of a distillation plant heated by diesel waste heat is shown. The salt water is distilled under a partial vacuum, which reduces the temperature required and increases the availability of waste heat, without requiring high pressure in the engine jacket. The major part of the waste heat is used to produce low pressure steam, (9 p.s.i. to 20 p.s.i. absolute), and a small part of the exhaust heat is used to produce steam at 250 p.s.i.abs. This high-pressure steam is needed for an air ejector which maintains the partial vacuum in the distillation system. The low-pressure steam is used to evaporate the salt water in the evaporator, and later condensed and returned to the engine-cooling water circuit, which is thus a totally enclosed circuit, with no danger of contamination with salt from the distillation circuit. The salt water used in the distillation circuit is preheated by using it as the cooling medium in the two condensers.

Table III shows the quantities of distilled water that can be produced from the waste heat available from the various types of engine described earlier.

TABLE III

DISTILLED WATER IN LB PRODUCED PER B.H.P./HR

ENGINE TYPE	LOAD		
	50%	75%	100%
Diesel naturally aspirated	1·80	2·23	2·42
Dual fuel engine naturally aspirated	2·62	2·39	2·24
Diesel supercharged ..	1·92	2·25	2·59
Diesel supercharged and after-cooled	2·02	2·38	2·58

The Application of the Dual Fuel Engine in Sewage Works

The dual fuel engine, as mentioned earlier, may be run either on diesel oil or on gas with a pilot charge of oil for ignition purposes. It may be switched over from one fuel to the other at any time without any delay. These attributes make it particularly valuable for duties where cheap gas is available, especially where supplies of gas are intermittent, liable to fail, insufficient for the full power requirements, or where the engine power is required before the gas supply is available. One or more of these conditions frequently applies in sewage works.

Modern sewage disposal undertakings use the activated sludge and digestor tank method of disposal. Bacteria reduce the bulk of the sludge and simultaneously liberate large quantities of sewage sludge gas of approximate calorific value 650 B.t.u./cu.ft. This gas is a waste product which can be used as an excellent fuel gas in a dual fuel engine, to provide power for the operation of the sewage works.

The sludge in the digestor tanks needs to be maintained at a moderately high temperature to obtain maximum activity of the bacteria. Waste heat from the dual fuel engines may be used to heat the sludge to the required value, so producing a substantial increase in the overall efficiency of the plant.

Fig. 6 shows diagrammatically an installation at a sewage works where the engines are to run initially on a heavy fuel oil, and as the installation progresses some engines will use sludge gas.

In this installation the gas supply is expected to be low, hence the desire to use a cheap grade of fuel oil. The water supply to the engine jackets is maintained at a high temperature, by using the exhaust gases to heat the incoming engine cooling water, to avoid cylinder corrosion problems with the heavy fuel. Thus the full amount of waste heat is finally given up at a low temperature, via heat exchangers, to the sludge digestor, which has to be held within moderate temperature limits (say 150°F. ± 10°). The use of an exhaust-gas water heater in the cooling water circuit is thus an unusual installation to suit the specific requirements for this station.

The heat-recovery and heat-requirement figures as originally estimated for this station and one

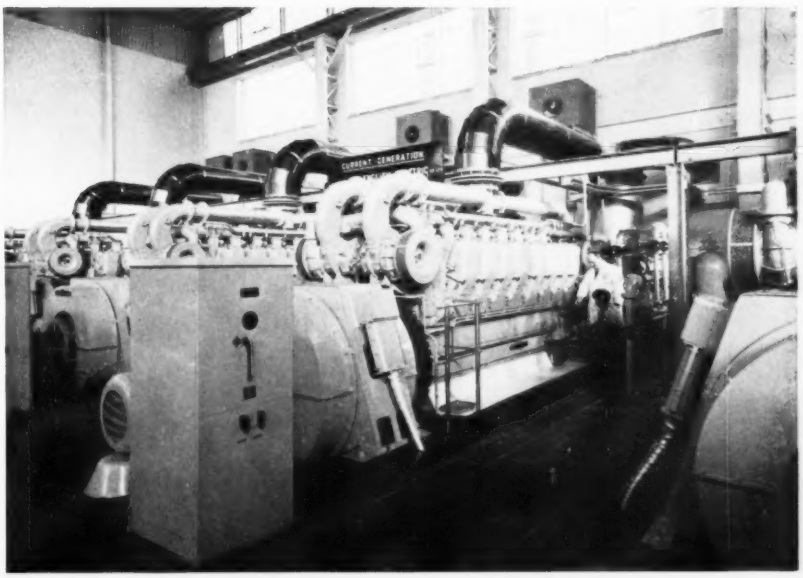


Fig. 7.
A diesel power station where the waste heat is used for space heating purposes. The engines shown are 1,000 kW supercharged machines running at 750 r.p.m. The ducting seen above the engines carries exhaust gases to waste-heat boilers, one of which is partly visible in the background

other are given below, with estimated fuel consumptions and gas production quantities.

	Case 1	Case 2
Waste heat to digestor 10^6Btu/h.p.	10·2	19·4
Anticipated requirements 10^6Btu/h.p.	13	20
Total fuel consumption 10^6Btu/h.p.	32·8	41
Gas available 10^6Btu/hr	9·4	33·6

It may be seen that wide variations in requirements occur, but that the waste heat recovery and use of sludge gas may be of considerable importance.

IN THIS PAPER an attempt has been made to indicate some of the ways in which the diesel engine may use to the greatest possible advantage the energy supplied as fuel. Every application needs to be considered on its own merits, to satisfy local requirements in the most economical way.

Acknowledgments

The authors thank the British National Committee of the World Power Conference for permission to publish this paper.

APPENDIX

Cost Estimates of the Application of Charge Refrigeration to Diesel Power Stations

Most of the methods of using waste heat from diesel engines described in the text are well-established engineering practice and have proved

CASE I

Power Generation Combined with Air Conditioning

Air temperature	100 F
Water temperature	85 F
Site rating of charge cooled engine	2,090 b.h.p.
Site rating of charge refrigerated engine (Charge air temperature)	2,290 b.h.p. 67 F
Station output peak requirements	11,000 b.h.p.
Station output base load requirements	9,500 b.h.p.
Air conditioning requirements	1,400–1,500 tons
(1) *Station with Six Charge Refrigerated Engines Including one Standby Set*	
Five engines at peak load 96% of rated output :	
Specific fuel consumption	0·372 lb/b.h.p./hr
' Cold ' available if all waste heat utilised	1,690 tons/hr
' Cold ' required for engine charge cooling	176 tons/hr
Minimum ' cold ' requirements, total	1,576 to 1,676 tons/hr
Say 2–500 ton refrigeration unit. 1–700 ton refrigeration unit.	
Cost : engines, alternators and switchgear	£228,000
Cost : refrigeration plant	£ 74,000
Cost : boiler plant	£ 15,000
Total	£317,000
(2) *Station with Seven Conventionally Aftercooled Engines*	
One standby set.	
Six engines at peak load of 87·5% of rated output :	
Specific fuel consumption	0·369 lb/b.h.p./hr
' Cold ' available if all waste heat utilised	1,650 tons/hr
Actual cold requirements	1,400–1,500 tons/hr
Say 3–500 ton refrigeration units.	
Cost : engines, alternators and switchgear	£259,000
Cost : refrigeration plant	£ 67,500
Cost : boiler plant	£ 17,500
Total	£344,000
Capital saving by use of charge refrigeration	£ 27,000

CASE II

Power Generation only, no other requirement

Ambient temperature	100 F
Cooling water temperature	85 F
Site rating of charge cooled engine	2,090 b.h.p.
Site rating of charge refrigerated engine	2,360 b.h.p.
(Charge air temperature)	45 F
Engine output	10,500 b.h.p.
Station output	7,430 kW
1) *Station with Six charge Refrigerated Engines*	
One Standby set.	
Five engines running at 89% load.	
Specific fuel consumption	0·367 lb/b.h.p./hr
Cold required for engine charge cooling	304 tons/hour
Say, 340 ton refrigeration unit.	
Cost : engines, alternators and switchgear	£228,000
Cost : refrigeration plant	£ 17,000
Cost : boiler plant	£ 5,000
Total	£250,000
2) *Station with Seven Conventionally Aftercooled Engines*	
One standby set.	
Six engines running at 84% load.	
Specific fuel consumption	0·368 lb/b.h.p./hr
Cost : Engines, alternators and switchgear	£259,000
Capital saving by use of charge refrigeration	£ 9,000
Running Costs per Year	
Station output per year	59·44 · 10^6 kWhr
1) Charge refrigerated engines :	
	£
Fuel oil 13,770 tons	344,000
Lubricating oil	12,000
Repairs and maintenance	26,000
Wages	20,000
Stores and water	8 000
Total	410,000
2) Conventionally aftercooled engines :	
	£
Fuel oil 13,807 tons	344,940
Lubricating oil	14,400
Repairs and maintenance	30 000
Wages	20,000
Stores and water	8 000
Total	417,340

themselves economically. The use of waste heat in an absorption refrigerator to cool the charge air of the diesel engine itself is technically feasible but needs more economic justification. Some justification is given below.

As exact values will vary from case to case, every installation needs to be estimated on its own merits, and generalisations may be misleading. However, if charge refrigeration makes possible a reduction in the number of diesel engine cylinders, especially when such reduction permits a reduction in the number of diesel engine/alternator sets, then there is a distinct possibility of a gain in capital cost and/or in running costs. Multi-engine

installations are most likely to be suitable for charge refrigeration. The cost of refrigeration equipment is relatively greater for small installations than for large ones, so that unless spare capacity is available for other reasons it would normally be more economical to install ample diesel engine capacity than to install a refrigeration unit. Thus an example of a single engine up-rated by this means was found to be unfavourable, the cost of the refrigerator being £40 for each additional horse-power obtained from the engine. Two examples where charge refrigeration would be economical are given below.

The first example is for a power station where the waste heat is used in an absorption unit for air-conditioning purposes. The intake air to the engines may be cooled to increase their rated load to deal with a peak output requirement, and during this period of peak output the additional waste heat available provides for the production of the extra 'cold' required by the engines, without reducing the air-conditioning capacity of the plant. It is necessary to install a larger refrigeration plant, but this cost is more than offset by the saving on an extra diesel engine, alternator and switchgear which would otherwise be required. Running costs during the major part of the year are identical with either installation. During peak load periods the charge-refrigerated engines consume slightly more fuel oil, but less lubricating oil. They may be expected to cost less in maintenance, as there is one less engine running. Thus, broadly speaking, the machinery and installation costs would be 8% lower when using charge refrigeration than when not so doing, and there would be a negligible, probably slightly favourable, difference in running costs. This example is tabulated in detail under Case I (p. 12).

The second example is for a power station where refrigeration plant may be installed for diesel charge air cooling only. Even in this case a saving of 3½% in the capital cost of machinery may be achieved by charge refrigeration. Estimated capital costs and running costs are tabulated in some detail for this installation under Case II. They show a small (2%) advantage for the charge refrigerated engines on running costs, i.e. 1·655 pence per kWh against 1·687 pence per kWh.

In these estimates the saving in capital cost is partly due to using the charge-refrigerated engines at a higher load factor than would be the case with the alternative installation, that is, the inherent necessity for increasing the size of an installation in finite steps is utilised. A comparison of the capital cost per horsepower installed in each case gives a more general appreciation, although it is emphasised that such generalisations are not a substitute for detailed study of particular requirements.

The installations in both Case I and Case II, with normal charge cooling by water at 85°F., would cost £17·7 for each horsepower installed. The charge refrigerated installations would cost £17·1 and £17·3 per horsepower installed in Case I and Case II respectively.

These examples do not include the cost of buildings. As the absorption refrigeration plant is relatively vibration-free, and is light in weight and small in size compared with the extra diesel alternator set required, the building costs would also be marginally in favour of charge refrigeration.

It may therefore be concluded that absorption refrigeration equipment, powered by waste heat, for charge cooling purposes, could advantageously be combined with power generation by diesel engines.

Bibliography

[1]*Bosnjakovic, F.*: "Techniche Thermodynamik", Textbook.

[2]*Crooks, W. R.*: "Combustion Air Conditioning Boosts output 50%". International Congress of Combustion Engines (C.I.M.A.C.), Germany, 1959, A-15.

[3]*Dorsey, W. G., Jr*: "Centrifugal Refrigeration". Presented at the A.S.R.A.E. Convention at Lake Placid, New York on 22nd June, 1959.

[4]*Eshaya, A. M.*: "Large-scale Demineralization of Sea and Brackish Water". Brit. Chem. Engng., vol. 4, April 1959.

[5]*Fountain, H. J.*: "The Utilisation of Waste Heat from Diesel Engines". Diesel Engine Users Association, March 1949.

[6]*Haseltine, T. R.*: "Rational Approach to Design of Activated Sludge Plants". Water and Sewage Works, vol. 28, May 1956.

[7]*Houston, T. R.*: "The Principles of Diesel Engine Waste Heat Recovery". Diesel Engine Users Association, March 1949. (Reprinted by Shell and B.P. Industrial Service).

[8]*Montgomerie, G. A., and Forbes, M. K.*: "Refrigeration of Charge Air for Diesel Engines". International Congress of Combustion Engines (C.I.M.A.C.), Germany, 1959, A-14.

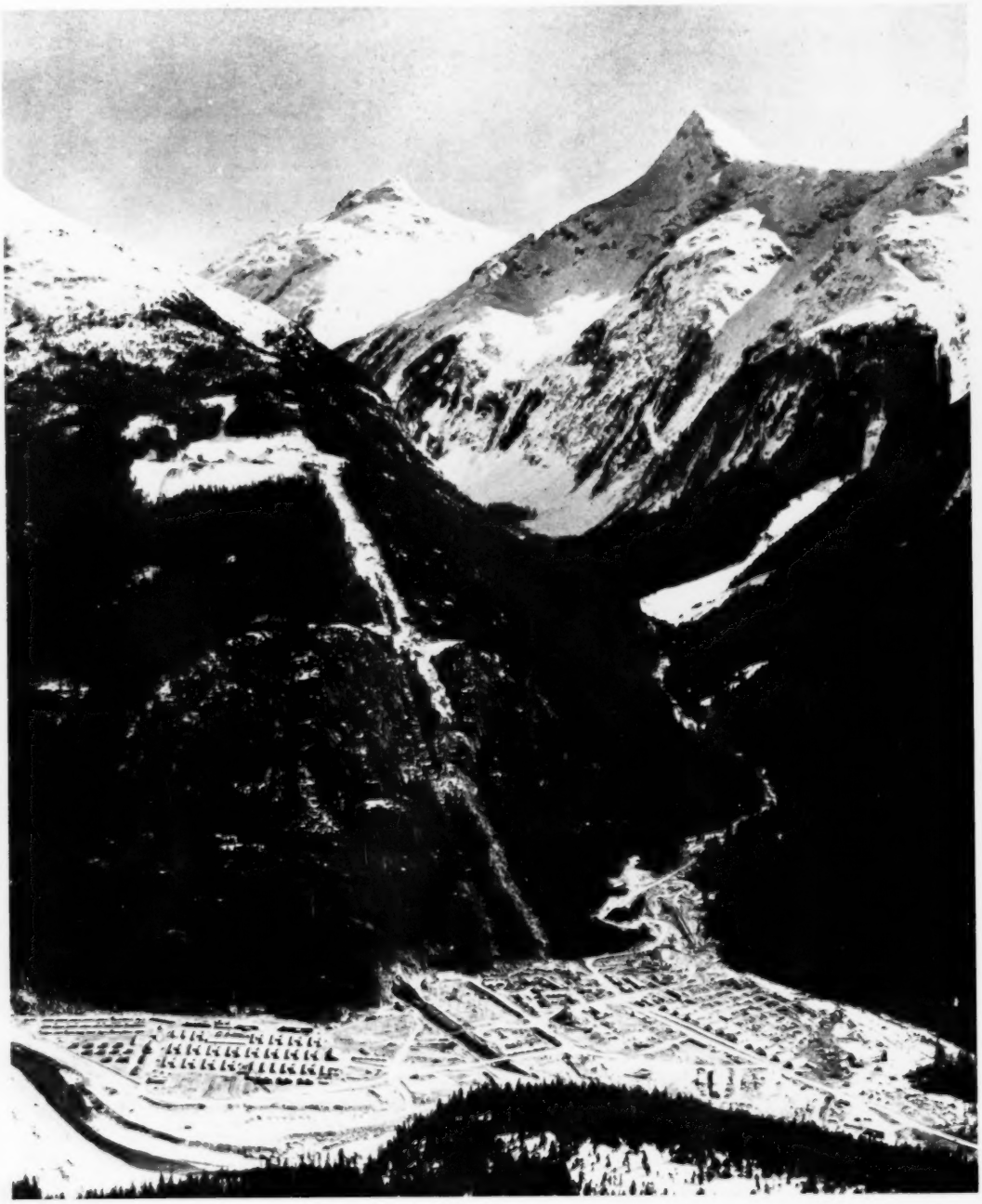
[9]*Potter, J. H.*: "The Utilisation of Waste Heat" (Bibliography 60 papers). Mech. Eng. Feb., 1959, p.58.

[10]*Pressel, F.*: "Methods for De-salting Seawater". V.D.I.Z., vol. 98, 1956.

[11]*Redfern, W. B., and Redfern, D. B.*: "Recent Development in Municipal Sewage Treatment Plants". Mun. Utilities Mag., vol. 93, Oct. 1955.

[12]*Silver, R. S.*: "The Sea can Meet the World's Increasing Water Demands". Engineering, 25th April, 1958.

[13]*Tufnell, R. M.*: "Waste Heat Recovery as Applied to Diesel Engines". J. of The Institution of Heating and Ventilating Engineering, vol. 26, Feb. 1959. pp. 285-298.



Kemano township and switchyard at the foot of Mount DuBose. The entrance to the power station can be seen at the mountain foot, in the centre foreground

Transfer Busbar Schemes for Kemano Power Station

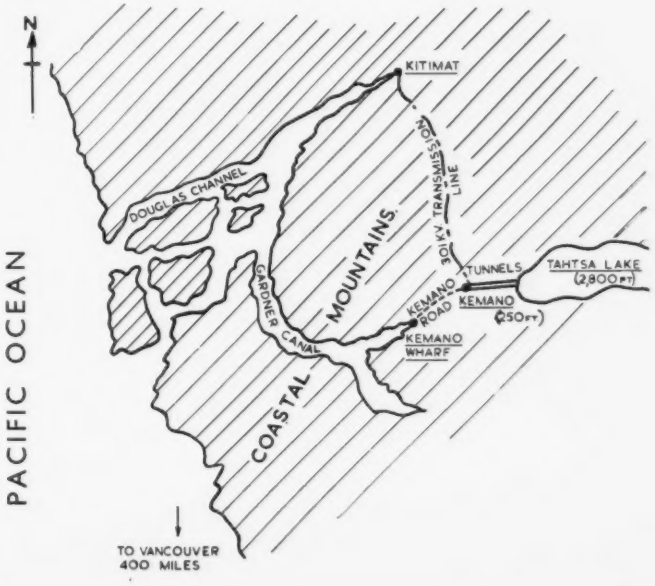
by D. W. SOUGHAN, A.M.I.E.E., formerly Assistant Resident Engineer at Kemano for the Aluminum Company of Canada Limited, now engaged on Consortium operations by arrangement with The English Electric Company.

POWER ENGINEERS throughout the world are familiar with the hydro-electric power stations of the Aluminum Company of Canada Ltd. (ALCAN) in British Columbia and Quebec, and in recent years the English Electric Group has been associated with two of these projects, namely the Kemano/Kitimat development in British Columbia and more recently the Chute-des-Passes power station in Quebec.

An article in The English Electric Journal of December 1956* described the two 106 MVA 13·8 kV 327 r.p.m. generators built by The English Electric Company for Kemano. In addition to these two British built machines, English Electric Canada supplied three 71 MVA 13·2/13·2/301·4 kV and two 70 MVA 13·2/275 kV 60 c/s single-phase transformers for Kemano and Kitimat respectively from their St. Catharines, Ontario, Works. The latter units, one of which is shown in Fig. 1b, were constructed with aluminium windings. The following discussion on subsequent developments at Kemano may therefore be of interest to readers of this journal.

Articles on the mammoth Kemano/Kitimat development have appeared in the world's technical press from time to time, and the natural obstacles which were overcome have been vividly illustrated in several documentary films. Since the pouring of the first aluminium ingot on the 3rd August 1954 the interest of the technical and lay public has naturally declined, notwithstanding the fact that seven generating units of about 110 MW rating each are now in service at Kemano.

Fig. 1a.—*The Kitimat-Kemano area, British Columbia*



* *Metcalf, E. T. 'English Electric generators for Kemano hydro-electric power station'. E.E. Journal, Dec. 1956, Vol. 14, No. 8, p. 24.*

By any standards, Kemano is an impressive example of an underground power station. Work started in the spring of 1951, and some three years later three generators were operating in a chamber 700 ft long, 80 ft wide and 120 ft high, 1,400 ft deep inside Mount DuBose. Considering the magnitude of the task and the ruggedness of the terrain such progress was remarkable. Construction in fact followed very closely on design, allowing little or no margin for second thoughts once technical instructions to the field had been issued.

Fig. 1b.—*One of the* '*English Electric*' 71 *MVA* 13·2/13·2/301·4 *kV single-phase transformers on its way from Kemano Wharf to Kemano power station.* (*See Fig.* 1a)

The task in 1951 was clear, and the fact that construction proceeded so rapidly is a considerable tribute to the pioneers engaged on the project at that time. Following operating experience it was decided in 1956 that the electrical layout at Kemano should be changed from a simple two-generator/one-transformer-bank arrangement to one providing transfer bus facilities for greater flexibility. Before discussing these changes however it is well to review the arrangement of the power station as it was originally constructed.

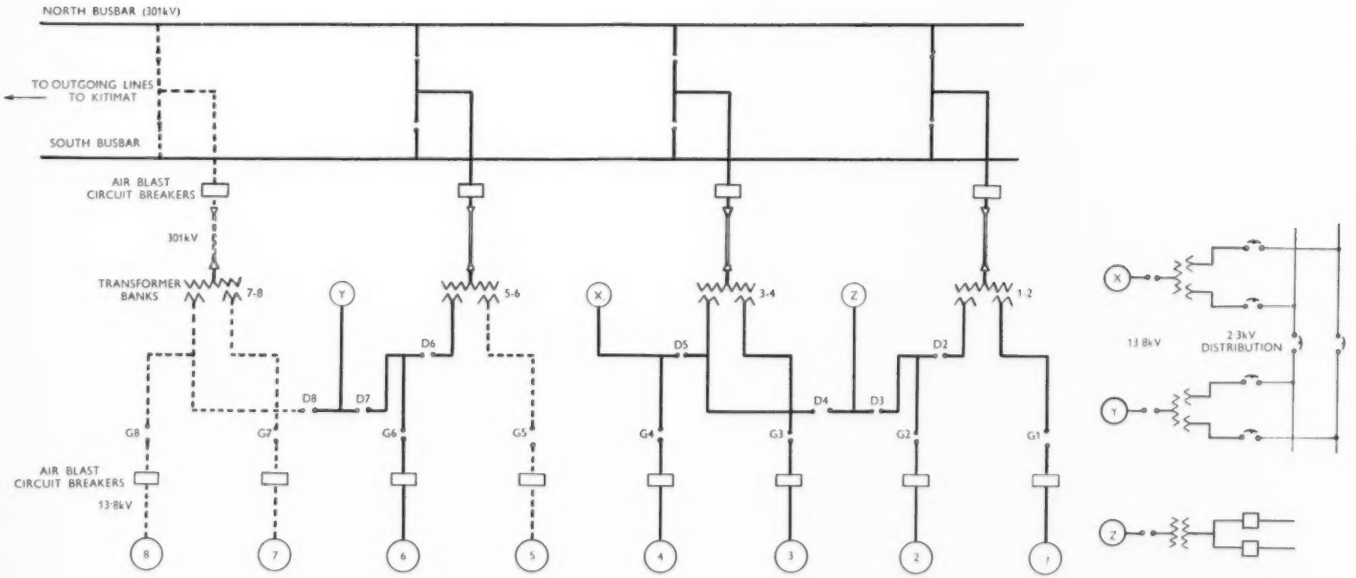
Electrical Design Features

Fig. 2 shows the electrical arrangements as designed and subsequently installed for units 1, 2, 3, 4, 5 and 6 at Kemano. The two-generator per one-transformer-bank arrangement was forced on the original designers by excavation considerations, the length of the power house being governed by the inflexible dimensions of the generating units.

The 13·2/13·2/301·4 kV double-primary/single-secondary single-phase transformer units are connected delta/delta/star and have a total bank rating of 213 MVA. There are no tap-changers on any of the windings. Cooling is of the oil-forced-water (OFW) design, employing two separate systems with external heat exchangers. A marked increase in kVA rating of approximately 30% is possible with both coolers operating at maximum water capacity.

Operating conditions at Kemano are dictated by the aluminium reduction line requirements at Kitimat, and the smallest single load that can be picked up or dropped off is about 70 MW. The voltage at the generator terminals therefore varies between wide limits (approximately from 13·2 kV to 14·7 kV) according to line and load conditions. Throughout this article the voltage at the generator terminals is taken as 13·8 kV, and at the transformer h.v. terminals as 301 kV.

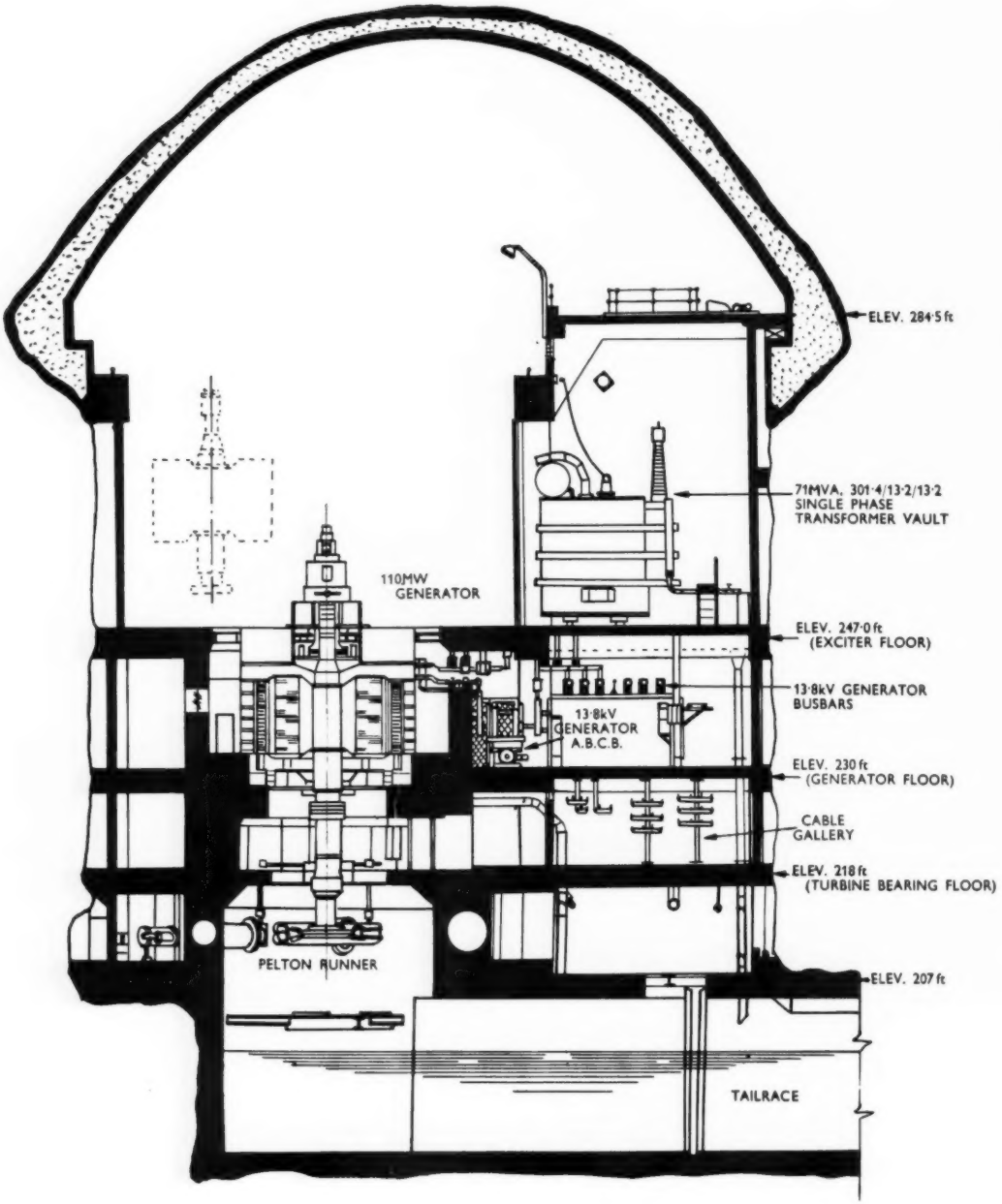
The generators have split-phase stator windings, and switching at the generation voltage of 13·8 kV is carried out by two 15 kV 4000 amp air-blast circuit-breakers operating in parallel as one electrical and pneumatic unit. The split phases are then paralleled on the line side of the generator circuit-breakers. The physical layout of a typical generating unit is shown in Fig. 3 and 4.



G = generator D = 'disconnect' (isolator)

Broken lines indicate future installation at time transfer bus scheme work incorporated.

Fig. 2.—Single-line diagram of original installation



A.B.C.B. = Air blast circuit breakers ELEV. = elevation

Fig. 3.—Cross-section of typical generating unit for original installation

Fig. 4.—Side view of typical generating unit during construction

The protective gear arrangements as planned and subsequently installed for the initial installation are as shown in Table I (p. 30), the modifications necessary to include the transfer busbars being indicated in the final column. These modifications were made with the object of providing adequate protection for all operating conditions, without unnecessary disturbance to the existing circuits, and are discussed later.

Transfer Bus Arrangements—General

To understand the considerations behind the decision to install transfer bus facilities for the first half (8 machines) of Kemano power house, it is necessary to review very briefly the original design concepts for the whole Kitimat/Kemano development.

The final arrangement of 16 units at Kemano requires two 10-mile tunnels from the Tahtsa Lake intake to elevation 2600 ft on Mount Du-Bose above Kemano. Four penstocks then descend to elevation 210 ft at the turbine spiral casing level, which in turn divide into four unit penstocks each feeding one turbine. The arrangement provides sufficient spare capacity to supply the minimum firm load at Kitimat from 12 units at Kemano, i.e. with one penstock, feeding four units, out of service.

For the first half of the development the smelter requirements at Kitimat will require a maximum of 7 out of 8 units in service at Kemano, and the basic design conceptions are therefore temporarily changed. With one tunnel only in service, the limiting factor on power output is not the water available—only plant serviceability. It is apparent therefore that all available plant must be fully utilized, and equipment outage reduced from a 220 MW 2-generator/1-transformer bank to that of one 110 MW generator.

Consider, for example, the following fault possibilities and their repercussions under the original arrangement for 8 units at Kemano.

(*a*) A fault on any generator would limit the output of its associated transformer bank to that of its accompanying machine.

(*b*) Damage to any single-core 301 kV cable would render one generator/transformer bank, or some 220 MW, unusable until the cable fault was rectified. Super-tension cable repairs involve specially trained personnel, and a cable fault could put two generators out of service for a considerable time.

(*c*) Although a spare single-phase transformer unit is available, damage to a transformer would effectively remove two generators from service until the spare transformer unit could be moved into position. Experience indicates this change can be accomplished in three hours.

Some form of transfer on the 13·8 kV and 301 kV sides was therefore clearly desirable and, following a period of study, the following arrangements were adopted :—

(1) A 13·8 kV 3-phase transfer bus erected at elevation 218 ft, coupled by rising busbars and isolators to each generator at elevation 230 ft, to provide interconnection between generating units. The switching arrangements for this bus are shown in Fig. 5, from which it will be noted that the switching of any generator on to the transfer bus is effected by 3-phase gang-operated off-circuit isolators labelled 'G' (generator), 'T'

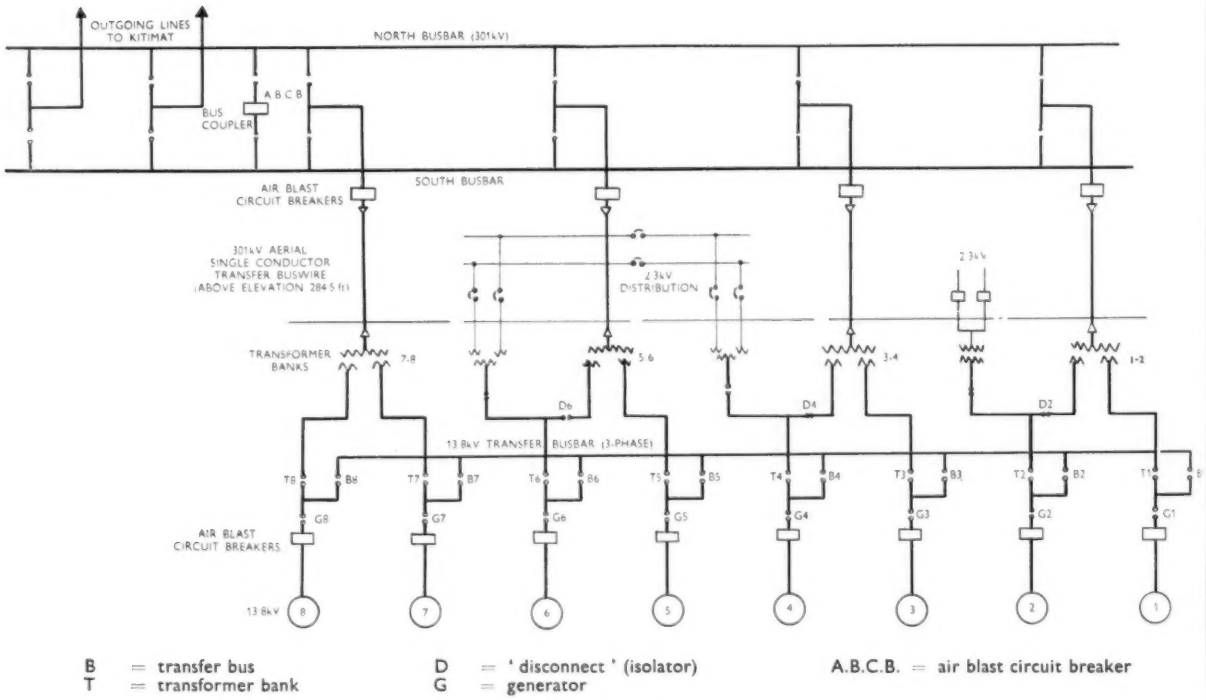


Fig. 5.—Single-line diagram with transfer busbars added

(transformer bank) and 'B' (transfer bus). This arrangement is identical for each machine, with isolators appropriately numbered, i.e. isolator G3 is the isolator for generator No. 3, and isolator B8 is the transfer bus isolator for generator No. 8, and so on.

(2) A 301 kV single-conductor aerial bus-wire strung above elevation 284·5 ft, together with a spare single-core 301 kV cable to the outdoor switchyard. This provides a means of replacing any faulty single-core cable by the spare cable. Changeover is effected by temporary connections at the cable terminations, an operation that can be rapidly carried out by a team of men, as the necessary bolted-type connection jumpers are always kept ready for use.

13·8 kV Transfer Bus Design

Electrical Considerations

It was necessary to calculate the expected transfer current in order to arrive at a suitable cross-sectional area for the transfer bus. It was then possible to examine critically the existing delta-connected bus work between two generators in any bank to ascertain whether or not extensive modifications would be required above elevation 230 ft.

Referring to Fig. 5, the power transfer with three generators operating in parallel is 330 MW. The current flowing in each 13·8 kV transformer winding is then one half of the total current from the three paralleled generators, or approximately 7000 amperes. The l.v. bushing current per phase (i.e. inside the bank delta connection) on each transformer l.v. winding works out directly as approximately 4000 amperes.

These conditions indicate that the transformers would be overloaded by about 60% above their nominal rating, but as in practice the transferred overload through a transformer bank is controlled, the transformer temperature rise is kept within acceptable limits.

The possible l.v. bushing current of 4000 amperes is about the maximum allowable by the various transformer manufacturers whose units are in service at Kemano.

The maximum possible current in the transfer bus under any operating conditions is difficult to calculate, but as a reasonable design basis the full output of two machines was considered to flow. Thus the bus was designed for a load current of about 9000 amperes.

All the existing bus work at Kemano is formed from standard aluminium channels mounted in pairs, and this arrangement was adopted for the transfer bus.

Two aluminium channels of 12 in. × 3·292 in. section in parallel form the bus, with a current rating of 8400 amperes for a 30°C rise over a 40°C ambient temperature which is usual in North America. This channel is the largest standard section fabricated in Canada and, with adequate ventilation, considerable overload above the nominal current rating for two paralled sections can be carried without undue temperature rise.

The transfer bus runs for a distance of approximately 420 ft at elevation 218 ft, and therefore expansion of the two 12 in. channels under load conditions had to be considered. The generators are spaced at 60 ft centres and individual connections from the generators are formed from two 7 in. × 2·404 in. aluminium channels welded on to the transfer bus by the argon-arc process.

The transfer bus can therefore be considered as rigidly fixed at the eight generator positions, and one expansion joint per phase is located mid-way between each generator. Several designs of flexible joint were considered and the arrangement finally adopted consists of ten 1·301 in. diameter aluminium cables (equivalent to 0·6 sq. in. copper conductors) each welded to a 9 in. × 2 in. × $\frac{3}{4}$ in. aluminium pad at either end, which is bolted to the bus sections with cables bent through a radius of 13 in. These ten flexible connections are arranged round the outside of the bus to cater for the considerable skin effect that becomes a factor at high alternating currents. This arrangement provides a flexible joint that is easily fabricated in the field from standard cable and aluminium strip, and is therefore most economical.

Expansion of the transfer bus is thus allowed to take place axially from the rigid generator rising connections over a distance of 30 ft in each direction. Support clamps are installed every 10 ft and allow axial movement of the bus, whilst providing firm support to resist short-circuit forces.

The existing bus sections between generators and associated transformers are of two 7 in. × 2·404 in. aluminium sections in parallel. Some rearrangement of these bars was necessary to incorporate the additional isolators.

The isolators originally installed were nominally rated at 6000 amp and it was thought that they would have to be replaced by others of a higher rating. Heat-run tests however confirmed that they could carry considerable overload without undue temperature rise, and they were therefore employed throughout the installation, and made the rearrangement of the bus work between generators a relatively straightforward matter.

Short-circuit MVA

It was necessary to calculate the short-circuit forces possible in order to design a mechanically sound transfer bus. These forces, being directly proportional to the square of the current and inversely proportional to the distance between conductors, were seen to be considerable.

Several switching combinations were studied and the following arrangement was adopted as a basis, yielding as it does a very pessimistic value for the short-circuit MVA possible. It provides for seven machines in service (i.e. one out of service as will normally be the case) with three of the generators in parallel on the transfer bus. The calculations were based on a symmetrical 3-phase fault on the transfer bus.

Considering the magnitude of the figures involved, negligible practical errors would result from approximating the relevant parameters. The following assumptions were therefore made :—

(1) That the sub-transient reactance of each generator is 21% at 110 MVA.

(2) That the reactance of each transformer bank is 10·5% at 110 MVA.

All other reactances were ignored since these assumptions give the most pessimistic results under fault conditions.

Fig. 6 gives the connections considered, and Fig. 7 an approximately equivalent circuit. The conditions shown are :—

(1) Generators 1, 2 and 3 connected to the transfer bus and paralleled with transformer bank 1-2.

(2) Generators 5, 6, 7 and 8 operating normally.

(3) Generator 4 out of service.

The symmetrical fault current under these conditions approximates to 100,000 amperes.

Mechanical Considerations

The prime consideration in the mechanical design of a busbar installation is to ensure that it will withstand the maximum possible shock loads that can occur under fault conditions. As previously mentioned, these forces are directly proportional to the square of the current and inversely proportional to the distance between the busbars.

For a new installation it is possible to study alternative busbar arrangements in the design stage and to arrive at the best scheme to meet technical and economic requirements. At Kemano no such liberties were allowed since it was essential to preserve the original installation as much as possible. With this in mind it was necessary to fit in the new transfer busbars with minimum disturbance to existing cabling, and to avoid any rock excavation which would have been required to give complete freedom of access.

Under 3-phase short-circuit conditions the centre busbar is subjected to forces from the outer phases. Using the most pessimistic formulae for the maximum force on the centre bar the following approximate figures were obtained :—

(*a*) 1100 lb per foot for a 36 inch spacing of the transfer bus.

(*b*) 1600 lb per foot for the 24 inch spacing of the existing buswork.

The support insulators used have a strength in tension of 12,000 lb and in compression of 80,000 lb. They have a cantilever strength of 8000 lb at $2\frac{1}{2}$ inches above the top. Accordingly the insulators were arranged to be subjected to a compressive load in the event of a short-circuit.

Physical limitations dictated that the transfer bus should be arranged as illustrated in Fig. 8. It will be noted that the supporting insulators are in compression.

With an insulator spacing of 10 ft the deflection should not exceed 0·05 in. under fault conditions, and the natural frequency liable to occur with this deflection is outside the range of 60 c/s and its harmonics.

Aluminium Busbars

As with many other practical engineering decisions, aluminium was chosen for the busbar material from other than purely theoretical considerations.

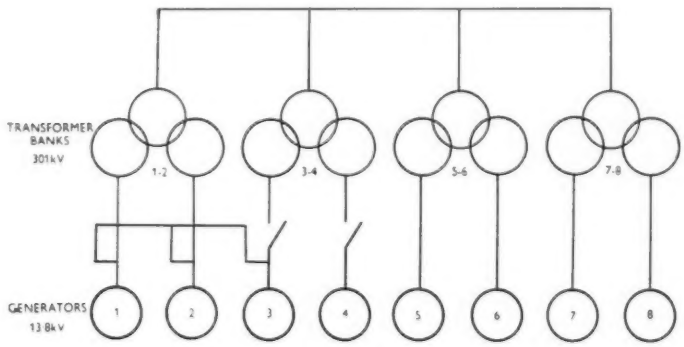


Fig. 6.—Simplified diagram for short-circuit calculations

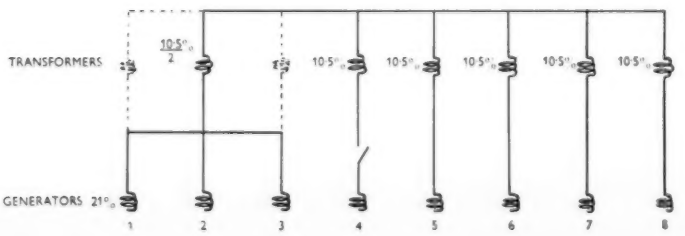
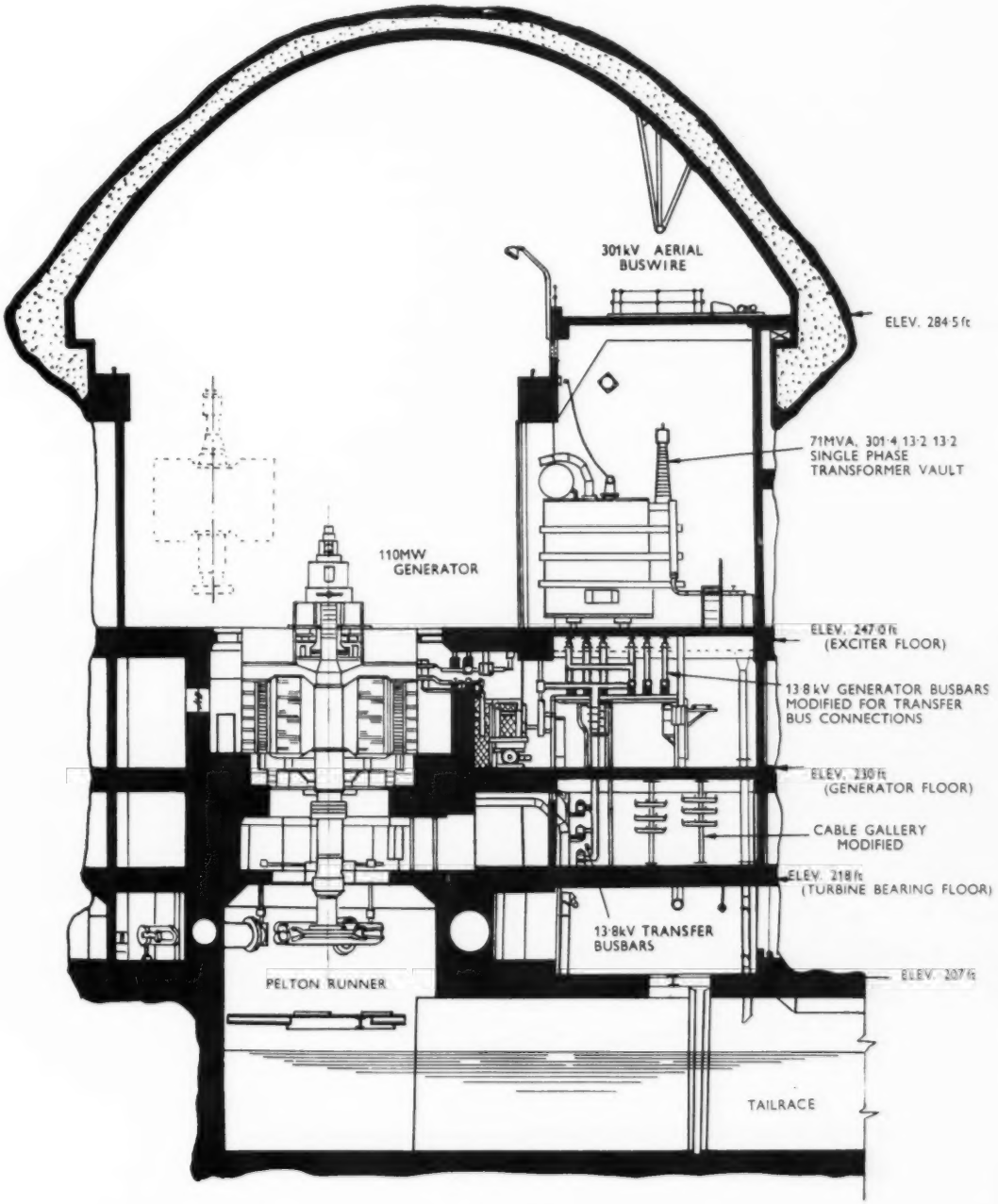


Fig. 7.—Equivalent circuit for Fig. 6.


301kV AERIAL BUSWIRE
ELEV. 284·5 ft
71MVA, 301·4, 13·2, 13·2 SINGLE PHASE TRANSFORMER VAULT
110MW GENERATOR
ELEV. 247·0 ft (EXCITER FLOOR)
13·8kV GENERATOR BUSBARS MODIFIED FOR TRANSFER BUS CONNECTIONS
ELEV. 230 ft (GENERATOR FLOOR)
CABLE GALLERY MODIFIED
ELEV. 218 ft (TURBINE BEARING FLOOR)
13·8kV TRANSFER BUSBARS
ELEV. 207 ft
PELTON RUNNER
TAILRACE

ELEV. = elevation

Fig. 8.—Cross-section of typical generating unit with transfer busbars added

Although an aluminium producer could hardly be expected to use copper, aluminium has several advantages ; its use for electrical purposes is now very widespread and may be expected to increase. Aluminium has less than one third the density of copper and, allowing for its lower conductivity, the weight of an aluminium busbar is only half that of a copper busbar of the same current-carrying capacity. Accurate cost comparison between the two materials for general purposes is difficult due to the wide fluctuations in the price of copper over the past decade or so, whilst for the same period aluminium prices have risen more or less uniformly. The present-day price levels, however, show a cost saving of approximately 50% in favour of aluminium.

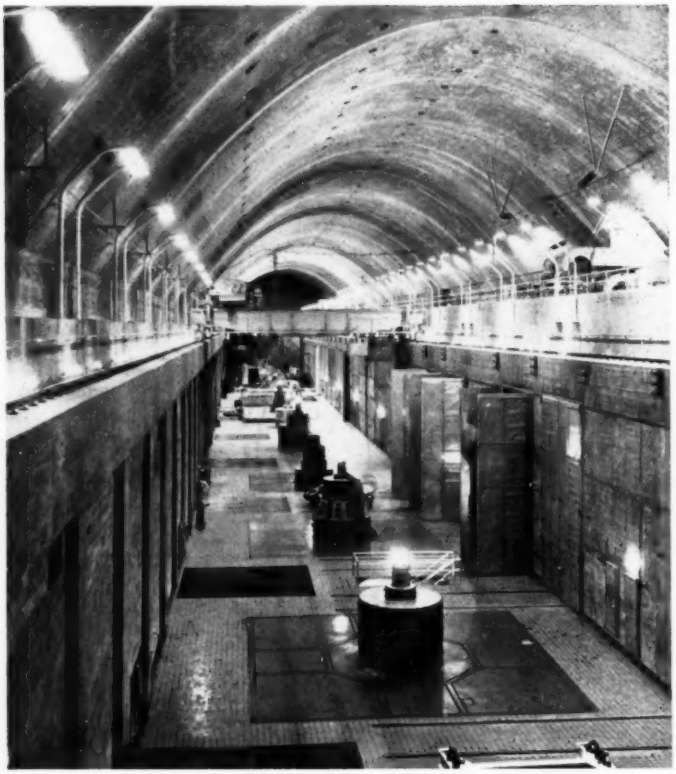


Fig. 9.—Kemano power station, showing 301 kV transfer bus (top right)

Aluminium busbars are employed to a greater extent in North America than in the United Kingdom, although their use is extending in the U.K. One of the objections sometimes raised by British engineers to the use of aluminium busbars is the difficulty of jointing and of making connections to copper. These objections, however, are easily overcome, and four welding processes can be applied when joining aluminium busbars. These are :—

1. Oxy-acetylene gas welding or brazing.
2. Metallic arc welding with flux-coated electrodes.
3. Inert-metal-arc (I.M.A.) welding.
4. Argon-tungsten-arc (A.T.A.) welding.

Finally, erection is much easier due to the lightness of the material, and in the case of the Kemano installation the question of joints between copper and aluminium did not arise.

301 kV Transfer Bus Design

The 301 kV transfer bus consists of one steel-cored aluminium conductor, identical to the conductors used for the greater length of the Kemano-Kitimat transmission line, of 1·5450 inch dia. (1590 circular mils cross-section).

The conductor is strung for a length of 440 ft, above elevation 284·5 ft, centrally along the line of the transformer vault hatch covers (Fig. 9). With only slight modification to the hatch covers, sufficient clearance was obtained for a bare connecting dropper to pass through the hatch opening to the appropriate transformer h.v. bushing.

The power house end of the 301 kV spare single-core cable terminates in a sealing-end bushing in a spare vault located between the vaults of transformer banks 5-6 and 7-8, and connection to the aerial bus is identical to that for the transformers.

Thus, to replace any faulty single-core cable by

the spare cable it is only necessary to carry out the following procedure at the power house end :—

(*a*) Disconnect the faulty cable from its h.v. transformer terminal

(*b*) Connect this transformer terminal to the aerial bus.

(*c*) Connect the spare cable to the aerial bus.

At the switchyard end the spare cable terminates in a sealing-end structure adjacent to the bus-tie air-blast circuit-breaker (which feeds through an isolator on to the north bus) at the centre or 'B' phase. Change-over procedure at this end is as follows :—

(*a*) Disconnect the faulty cable from its circuit-breaker.

(*b*) Connect the spare cable to the appropriate phase being replaced, on the bus-tie circuit-breaker.

(*c*) Close the north bus-tie isolator.

(*d*) Close the bus-tie circuit-breaker.

(*e*) Close the bank circuit-breaker (i.e. with only two healthy cables in circuit).

(*f*) Synchronise across the 13·8 kV generator circuit-breakers.

Protective Circuits Affected

With reference to Table I, when the spare cable replaces a faulty cable the following protective circuits are affected :—

1. Cable oil differential alarm.
2. Transformer differential.
3. Cable differential.
4. Line overcurrent.

The 301 kV cables at Kemano are of the Pirelli oil-filled type and for the majority of circuits a differential oil-pressure alarm scheme is incorporated for all three phases. The spare single-core cable, whilst of the same design, cannot be readily incorporated in any 3-phase bank while at the same time retaining the oil-differential alarm feature for the two healthy original cables plus the one spare. Visual indication of oil conditions is therefore relied upon for all three phases of the circuit in the event of the spare cable being utilised.

The transformer differential, cable differential, and line overcurrent protective circuits are rendered inoperative when the spare cable is in service, since to cater for all interconnection possibilities whilst retaining essential simplicity for change-over is impracticable.

Protection for a two-generator/one-transformer bank with the spare cable incorporated is by master earth and transformer h.v. neutral relays. The master earth relay trips all generators, whilst the transformer h.v. neutral relay trips the 13·8 kV and 301 kV sides of the bank.

The auxiliary wiring of the bus-tie breaker includes a unit trip sequence relay contact which, by manual operation of change-over switches, includes the bus-tie breaker in this relay zone.

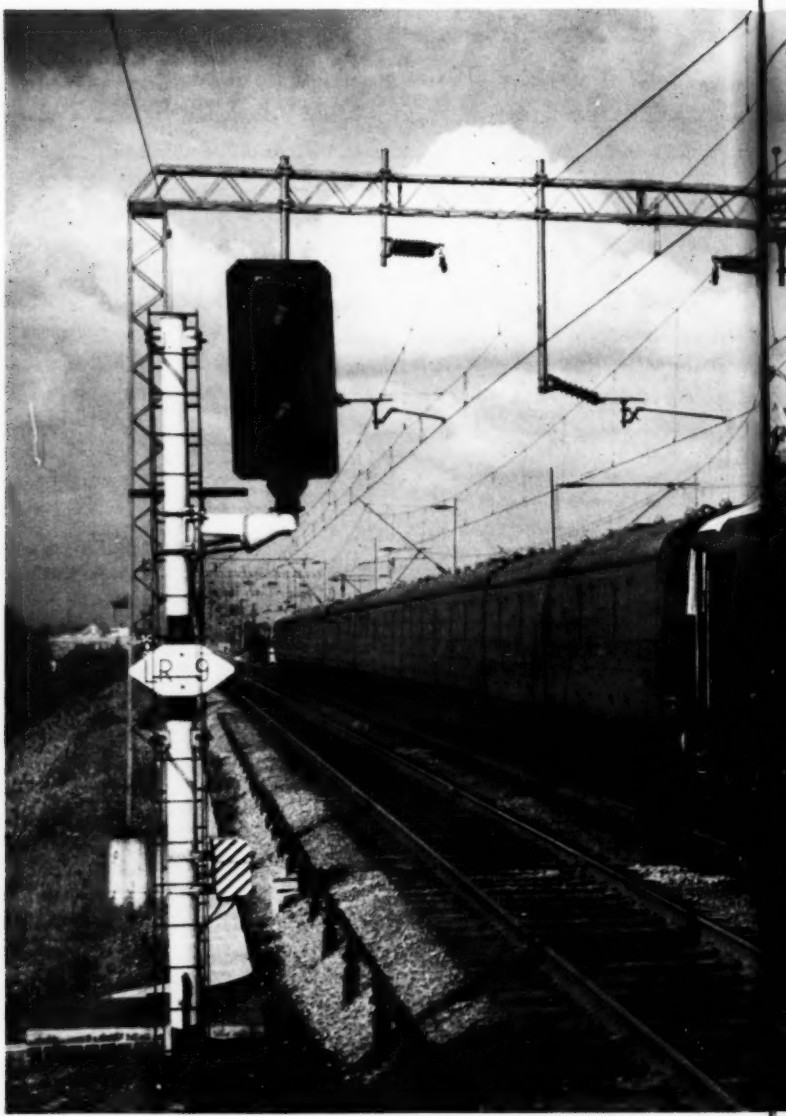
It was desirable, of course, to introduce the transfer busbars with the minimum disturbance to the original installation, while providing adequate protection for all operating conditions.

Summary and Operating Aspects

The preceding discussion covers the salient design features of the modifications required to provide Kemano power station with two transfer busbar schemes. Although the additional flexibility of the new arrangements may be of use for normal operation, the main function of the schemes is to provide interconnection, and thus optimum use of healthy plant, in the event of plant failures. The schemes therefore being for emergency use, change-over of main circuits and violation of protective circuits are by hand, and no further complications by way of interlocks and remote control of isolators were introduced.

When the installation work for the 13·8 kV transfer bus is completed it will be permissible to remove isolators D4 and D8 as shown in Fig. 2 since, with the transfer bus available for interconnection, the final arrangement as shown in Fig. 5 will be sufficiently flexible for alternative feeding of the auxiliary transformers.

Ultimately, the mimic diagram on the main control desk will be modified to show the 13·8 kV transfer bus on a single-line diagram. Since the 301 kV transfer bus and spare cable form a single conductor entity, which may be connected



One of the fifteen 'English Electric' 3,000 h.p. A
on the London-Manchester-Liverpool 25 kV 50 c/s
recently electrified Manchester-Crewe section of

Twelve of the locomotives ordered are type 'A'
of 100 m.p.h. and the latter 80 m.p.h. Both types

o. Motives being supplied to British Railways for service c/s first of these locomotives are now operating on the of t

A' are type 'B', the former having a maximum speed pes Bo wheel arrangement.

TABLE I

PROTECTION, WITH MODIFICATIONS FOR TRANSFER BUSBAR SCHEMES

Protection	Function	Modifications
Field failure	Trips 13·8 kV generator circuit-breakers	None
Field earth detector	Indication only	None
Generator overcurrent ..	Trips (*a*) 13·8 kV generator circuit-breakers (*b*) Exciter field ,, ,, (*c*) Generator field ,, ,, Actuates Turbine governor solenoids	None
Generator split-phase ..	Trips (*a*) 13·8 kV generator circuit-breakers (*b*) Exciter field ,, ,, (*c*) Generator field ,, ,, Actuates Turbine governor solenoids	None
Generator differential ..	Trips (*a*) 13·8 kV generator circuit-breakers (*b*) Exciter field ,, ,, (*c*) Generator field ,, ,, Actuates Turbine governor solenoids	None
Transformer differential ..	Trips (*a*) 301 kV circuit-breaker (*b*) 13·8 kV generator circuit-breakers (*c*) Generator field ,, ,,	(1)
Cable differential	Trips (*a*) 301 kV circuit-breaker (*b*) 13·8 kV circuit-breakers (*c*) Generator field circuit-breakers	(2)
Transformer earth fault ..	Trips (*a*) 301 kV circuit-breaker (*b*) 13·8 kV circuit-breakers (*c*) Generator field circuit-breakers	None
Generator earth fault ..	Trips (*a*) 13·8 kV generator circuit-breakers (*b*) Exciter field ,, ,, (*c*) Generator field ,, ,, Actuates Turbine governor solenoids	None
Line overcurrent	Trips (*a*) 301 kV circuit-breakers (*b*) 13·8 kV generator circuit-breakers (*c*) Generator field ,, ,,	(2)*
13·8 kV transfer bus differential	Trips (*a*) 13·8 kV generator circuit-breakers (*b*) Exciter field ,, ,, (*c*) Generator field ,, ,, Actuates Turbine governor solenoids	†

(1) Protective circuits modified to include the 13·8 kV transfer busbars in their protective zone by connecting additional current transformers in the vertical generator connections to the transfer busbars between elevations 218 and 230 ft.

(2) Original protective circuits rendered inoperative when the 301 kV transfer bus-wire and spare cable is in service, by short-circuiting the appropriate current transformers.

* Interconnected with other generator/transformer banks.

† This is a new installation, and the selection of the appropriate generator/transformer bank is effected by auxiliary switches on the 'B' and 'T' isolators.

to any generator/transformer bank and to any phase, it will be impracticable to show this on the diagram.

The addition of these transfer busbars provides an interesting example of practical field design somewhat more involved than that normally met by the site electrical engineer. It illustrates the necessity for coupling theoretical considerations with the severe physical limitations found in an underground power station. As with all power station modifications, the work was carefully planned to avoid costly shut-downs and to minimise civil engineering work.

Due regard was naturally paid to economic considerations, but no figures are given here since labour and material costs in an isolated Canadian valley bear no relation whatsoever to British practice. Furthermore, it was possible to utilize a good deal of surplus material from the original construction, which perforce made the cost estimates rather conservative. There was therefore ample scope for the design team to exercise the true function of the engineer, which is to design and build economically.

Acknowledgments

Thanks are due to the Aluminum Company of Canada Ltd. for permission to publish the information contained in this article, and for the use of the illustrations. Useful comments have been considered from colleagues in The English Electric Company and from Mr. A. G. Thomas, co-author of 'Aluminium Busbars', to whom the author's thanks are also due.

Developments in Electrical Equipment for Reversing Plate Mills

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THIS PAPER REVIEWS *recent developments with particular reference to control systems. Certain aspects have been selected for consideration which may be new to many, or which may still be controversial. The first half of the paper considers features of interest in main and auxiliary drives for large plate mills. The second half treats in more detail the problems of automatic control.*

THE MAIN DRIVE

Power requirements

WHEN CONSIDERING ANY DRIVE the power requirements and control requirements must be decided first. In the case of plate-mill drives the rating of motors necessary to carry out the rolling duty cycle must be determined first.

For known rolling programs the power requirements of the drive can be calculated fairly closely. Considerable information is available already on this subject.[1-4] Normally it is impossible to foretell the worst duty the mill will be called upon to perform during its life. The results of any calculations should therefore be compared with known practice. Table 1 gives the ratings of some typical modern plate-mill drives.

Method of rating

Occasionally misunderstanding still occurs over the output capabilities of a motor having a given

TABLE I

TYPICAL MODERN PLATE-MILL MAIN DRIVE RATINGS

MILL					DRIVE				
Nominal roll width (in)	Work roll dia. (in)	Type	Base speed (ft/min)	Top speed	Rms. rating, (hp)	Base speed (Rev/min)	Top speed	Cut-out torque, (tons-m)	Physical arrangement
160	38	4-high, single stand	350	900	8,000	35	90	492	Twin motor (DA)
126	42	2-high, roughing	440	880	4,600	40	80	246	Single motor (SA)
150	39	4-high, intermediate	410	1,025	9,200	40	100	492	Twin motor (SA)
150	36·5	4-high, finishing	435	1,090	9,200	40	100	492	Twin motor (SA)
132	39	4-high, single stand	460	815	10,360	45	80	492	Twin motor (SA)
144	38	4-high, single stand	400	1,000	10,000	40	100	492	Twin motor (SA)
98	32	4-high, single stand	375	750	5,000	45	90	240	Single motor (SA)
90	27	4-high, intermediate	300	535	3,650	42	75	183	Single motor (SA)
90	27	4-high, finishing	390	530	2,650	55	75	100	Single motor (SA)
86	37	Reversing rougher and plate mill	485	1,160	7,000	50	120	300	Single motor (SA)

SA = single armature. DA = double armature

name-plate rating. A note on this point is therefore appropriate, but first it is desirable to define terms.

R.M.S. (continuous) rating—The maximum power which the motor will develop continuously at rated speed without exceeding its rated temperature rise. It is also the horsepower equivalent at rated speed of the maximum value of r.m.s. torque that a duty cycle can have without the motor exceeding its specified temperature rise.

Sustained overload—An overload sustained for a sufficiently long period (usually specified) to affect appreciably the temperature. Large reversing-mill motors in the U.K. usually have a sustained overload capacity of 25% for two hours.

Working peak torque—The maximum torque which the motor can develop for a specified number of seconds, repeatedly as part of a regular duty cycle. The factor determining this on d.c. reversing-mill motors is commutation.

Cut-out or circuit-breaker torque—The maximum momentary torque that the motor can occasionally develop with no sign of electrical or mechanical damage. The overload protection is set to trip at this value.

In the U.K. up to 1955 the relevant British Standard for large mill motors was BS.169 (1925). The salient features of this for present considerations were that it specified a sustained overload capability of 25% for two hours and a momentary test overload of 100% for fifteen seconds. The armature temperature rises specified were 40°C for class A and 50°C for class B above an ambient air temperature of 40°C. Reversing-mill motors were designed to this standard except for the peak overloads which were normally a working peak of 2½ times full load torque and a cut-out peak of three times full load torque.

It had been realised for many years that the sustained overload capacity was an unrealistic requirement for many industrial drives and that the temperature rises specified in BS.169 were unduly conservative for many applications. Following a study of this problem BS.2613 was introduced in 1955, replacing BS.169 and also BS.168 and 226. Machines specified in accordance with this specification have no sustained overload capacity and have a continuous rating which is that equivalent to the maximum temperature rise above 40°C that can be maintained continuously and still give a satisfactory operational life to the machine. This is termed the 'continuous maximum rating' (CMR). The specification therefore allows no sustained overload and the momentary test overload for d.c. machines is only 50% for fifteen seconds. The armature temperature rises above 40°C are 55°C for class A and 75°C for class B, by thermometer.

From 1955 to date the standard British practice for reversing-mill motors has been to design in accordance with BS.2613 except for temperature rises and overloads. For these factors the standard practice which existed before 1955 has been retained. There have been three main reasons for this. Firstly it was generally agreed that for heavy-duty motors where reliability was of prime importance it was desirable to be conservative in the temperature at which they were operated to ensure maximum reliability. Secondly, past experience has shown that it is often useful to have an inherent sustained overload margin in the motor for future contingencies and it was felt to be easier to do this by specifying a lower temperature rise than specifying a higher rating ; previous practice was based on the lower temperature rise. Thirdly, in many primary reversing mills the motor size was determined mainly by the peak load, and the r.m.s. load to which it is subjected is not likely to be much more than one-third of the cut-out torque. However, larger ingots and tandem rolling are changing this situation.

Curves A and B in Fig. 1 show the continuous torque and working peak torque characteristics respectively for a typical U.K. reversing-mill motor with a speed range of 2½—1. Between base speed and twice base speed the torque falls inversely in proportion to the increase in speed above base speed owing to the reduction in field flux. Above twice base speed the cut-out torque starts to fall away more rapidly because at these higher speeds the worsening conditions for commutation cause the cut-out armature current to be reduced at the same time as the field flux is falling.

Standard U.S. practice for reversing-mill motors is set down in standards published by the National

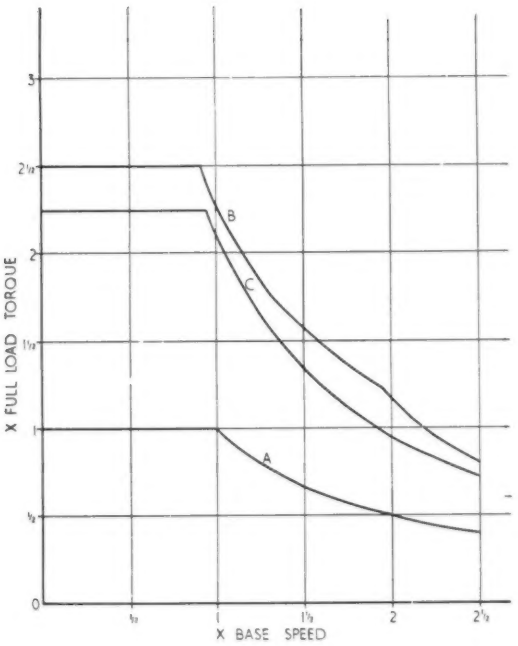


Fig. 1.—Reversing motor torque characteristics (Note : Curves show motor torque capability and modifying effect of control scheme)

Electrical Manufacturers Association[5] and is based on a 50°C rise for armature windings having class A insulation with no sustained overload. Curve C in Fig. 1 gives the cut-out torque speed characteristic set down by NEMA.

Until recently, other European practice tended to line up very closely with the U.K. practice but was rather more flexible in designing the motor to suit a particular job and in recent years this tendency has increased.

Up to the present there has been no disadvantage in adopting these conservative ratings for reversing-mill motors. Nevertheless, it is important that the margins which are being built into the machines are recognised when making decisions as to the size of motor that should be used. Three factors now affecting the design of electrical equipment for plate mills make it desirable that future policy towards rating standards should be flexible.

The first of these is the advent of automatic control. As mentioned later in this paper fully automatic control will make the duty cycle for a reversing mill far more predictable, and it will then be desirable that the factors affecting the continuous and peak output capabilities of a motor are clearly recognised and correctly evaluated. The second is the increasing importance of dimension limitations as the rating of motors for a given size of mill increases. The third is the use of mercury-arc convertors for the supply of large plate mills, a use which is undoubtedly going to increase. To attain the most economical drive unit, the convertor unit and the drive motor that it supplies must be correctly matched. Also, a standard which may be economical to maintain in the case of motors and generators may be uneconomical in the case of static convertors.

AUXILIARY DRIVES

Power requirements

The total time for which a plate is actually between the main mill rolls is often less than half the time required to roll the slab to the required plate product. The rest of the time is taken up in removing the finished plate from the mill, bringing a new slab up to the mill, and handling the piece between passes. The time taken to perform these functions therefore has a very great bearing on the output of a mill and this time is very much affected by the performance of the auxiliary drives. To enable the time to be kept to the minimum the drives must give rapid response of the auxiliaries to the operator's instructions. This means ample horsepower and good control.

The auxiliaries put no work into the piece being rolled. Therefore the power of the auxiliary drives is determined by the electrical and mechanical losses that occur within the auxiliary systems themselves. These comprise the normal running losses plus the additional losses that occur during acceleration and deceleration of the auxiliary drive and mechanism, and also the piece where this is applicable.

In modern mills the peak power required is largely determined by the acceleration and deceleration torques required to give the necessary response. Also, because the acceleration and deceleration periods form a large part of the total operational time of the auxiliaries the r.m.s. rating of the drive

is also mainly determined by these torques and the frequency with which they occur.

In a typical 144-in plate mill with individual roller drives, the roller motors for the main tables are AISE frame 612 and to attain the maximum required rate of reversal they must develop a mean reversal torque of twice the standard full load rating for this frame.

Care should always be taken to check both the peak torque required to give the desired response and the r.m.s. torque of the heaviest duty cycle. Either can be the determining factor in motor frame size according to the type of mill and its duty.

Motors and rating

General practice for large plate-mill auxiliaries is to use d.c. mill-type motors rated and dimensioned to AISE standards.[6] For reasons mentioned later the majority of auxiliaries are variable voltage and the motors used are standard 230 V shunt-wound '600 series', often run up to twice speed on double voltage to attain the maximum operating speed required.

The frequency of the duty cycle on many plate-mill auxiliaries is such that the r.m.s. torque rating would greatly affect the motor size if a totally enclosed motor were used. The motors for these auxiliaries are therefore force ventilated. This is now almost always so in the case of screw-down and roller-table drives. Where the motor inertia is a major factor in the total inertia of the auxiliary system, forced ventilation is also desirable to keep this inertia to a minimum by keeping the motor frame size to a minimum. In certain limiting cases the desired response could not be obtained without forced ventilation.

To achieve forced ventilation the general practice is now to provide an opening on the under side of the motor frame at the commutator end. The air is ducted to the opening through the motor bed plate and escapes out of the motor into the mill through holes at the opposite end of the motor.

As is the case with large slab mills, present practice with many large plate mills is to use a separate motor to drive each roll of the main table. Because of the space limitations which often occur in this application, modified mill-type motors of special electrical and mechanical design have been made available in the U.K. and in the U.S.A. for this application. These motors have only a single shaft extension and the terminal box is on the rear end shield. Thus the overall diameter is kept down to a minimum, enabling the minimum motor centres to be obtained.

POWER SUPPLY : MAIN DRIVE

Motor-Generators

The first large electric reversing-mill drive was installed on a cogging mill in Austria in 1907.[7] From this date until the last decade the Ward-Leonard system of control using an Ilgner set to supply the main drive has predominated for large reversing mills.

The d.c. motor with speed control by variation of its armature voltage supplemented by field weakening at full voltage cannot be rivalled for this type of drive. No other form of control can match the performance of this system, either in the degree of control that it gives or in the low level of energy losses.

The motor-generator (m-g) set has proved a very effective way of providing the variable voltage d.c. power. Further, until very recent years power supply systems in the U.K. had not sufficient capacity to absorb directly the very 'peaky' load of a large reversing mill. It was therefore necessary to provide some form of buffer energy store. A mechanical store in the form of a flywheel has proved to be the only practical way of doing this.

As the capacity of the power supply systems in some parts of the world increased it became permissible to transfer the peaks of a large reversing mill straight back to the supply system. The flywheel was therefore omitted and a simple m-g set used, driven by either a synchronous motor or an induction motor. One of the major advantages gained in so doing was the omission of the rotor losses which occurred in the induction motor rotor circuit when the speed of the Ilgner set dropped to release energy from the flywheel.

Mercury-arc Convertors

Where static forms of energy conversion can be used they offer several advantages over systems using rotating machines :—

(i) They convert the energy more efficiently.
(ii) Their light load losses are less.
(iii) Less heat and noise are produced.
(iv) Less maintenance is required.
(v) Simpler foundations are required and a more flexible layout can be adopted. Also, simpler building structures may be used, since the only heavy lifts are the drive motors.
(vi) Many static systems enable faster response control systems to be provided.

Against this, static devices have three main disadvantages which until recently have retarded their full application for reversing-mill drives :—

(i) A buffer energy store, equivalent to the addition of a flywheel to an m-g set, cannot be provided. The power supply system must therefore take the full peak loads of the mill.

Also the most effective systems of voltage control give poor power factor at low voltages. This can considerably increase any voltage dips caused by the mill load peaks.

(ii) Harmonics are introduced into the a.c. supply system.
(iii) Their uni-directional characteristics introduce extra complexity into the control, where reversing torques are required.

Many supply systems are now able to supply large reversing-mill drive loads without the necessity of a buffer energy store, and to absorb satisfactorily the harmonic effects which occur. This has removed the first two disadvantages and has opened up the possibility of using static conversion devices. The only static conversion equipment at the moment that can meet the requirement of reversing mills is the mercury-arc convertor, and several reversing mills are now being or have been installed in the U.K. with their main drives supplied from mercury-arc convertors. The largest is a twin drive for a 132-in reversing plate mill with an r.m.s. rating of just over 10,000 h.p. which will be going into operation in the middle of this year.

Estimated energy consumption figures for typical plate-mill drives supplied from Ilgner sets, and alternatively from mercury-arc convertors, show savings in energy costs of up to 10% or more in favour of the convertor.

In addition to the limitation caused by the supply systems there was also a natural conservatism to adapt new devices to such important drives. Modern variable-voltage feedback control systems acting through d.c. generators leave little to be desired in the control they provide for large reversing drives. Further, the large number of such systems now in use has meant that the control systems now available are the result of a steady development over a number of years and are a very effective tool which is reliable and simple for the job it does. However, considerable operational experience has been gained in the use of mercury-arc convertors to supply continuous mills in the U.K. and considerable experience of their use in reversing mills elsewhere in Europe has proved their suitability and reliability in this field. With this experience now available, and in view of the advantages offered by the use of mercury-arc convertors, the possibility of using them is now almost always considered in any new reversing-mill project. The load cycle of a large plate mill may, however, be excessive for the capacity of the supply system in some cases. A careful consideration of the effect of the convertor-fed mill on both the works supply system and the area supply system must therefore be made.

POWER SUPPLY : AUXILIARIES

Up to the late 1930's plate-mill auxiliaries were driven by a.c. or d.c. motors fed from the works distribution systems. In the U.K. d.c. motors were more usual because of their better control characteristics.

In recent years it has become general practice for most of the auxiliaries associated with the operation of large plate mills to be variable voltage controlled. This practice has been adopted for reasons of both economy and control, as is explained later. In most installations at present the variable voltage supply is achieved by the use of m-g sets driven by synchronous motors or induction motors. Table II gives some typical ratings for large plate-mill auxiliaries and the arrangement of the supply m-g sets.

TABLE II

TYPICAL RATINGS FOR LARGE PLATE-MILL AUXILIARIES

MILL			AUXILIARY DRIVE								
Nom. roll width (in)	Appx. max. slab weight (tons)	Type	Duty	Total no. of motors	AISE frame	HP of each motor, 230 V rating	Rev/ min of motor, 230 V rating	Rev/ min of motor at max. operating voltage	Control	Appx. speed of motion at max. motor speed, (ft/min)	Remarks
150	10	4-high, inter-mediate rougher	Ingoing main tables	4	614	100	485	970	WL	800	Tapered rollers for turning
			Breast rolls	6	618	200	415*	150	WL	800	* 460 V rating
			Outgoing main table	2	614	100	485	970	WL	800	
			Screwdowns	2	616	150	460	460	WL	31¼ in/min	
			Sideguards	4	606	25	650	650	Con-tactor	200	
144	22	4-high, single stand	Main tables	34	612	28·7 hp at 211 rev/min on max. operating voltage (215 V)			WL	..	Special individual roller drive motors
			Screwdowns	2	616	150	460	920	WL	..	
			Sideguards	4	610	50	585	585	Con-tactor	..	
			Approach table	16	610	18 hp at 211 rev/min on maximum operating voltage (215 V)			WL	..	Special individual roller drive motor
			Runout tables (Nos. 1-5)	79	610	18 hp at 211 rev/min on max. operating voltage (215 V)			WL	..	Special individual roller drive motor
			Runout table No. 6	24	608	13·3 hp at 240 rev/ min on max. operating voltage (215 V)			WL	..	Special individual roller drive motor
132	20	4-high, single stand	Main tables	30	614	35 hp at 174 rev/min at max. operating voltage			WL	816	Special individual roller drive motors. Tapered rolls on ingoing and outgoing tables
			Feed rolls	6	618	75 hp at 156 rev/min at max. operating voltage			WL	816	Special individual roller drive motors
			Screwdown	2	618	200	420	1,100	WL	75 in/ min	Automatic position control
			Sideguards	4	610	50	550	275	WL	195	Automatic position control
98	..	4-high, single stand	Work and turn table	4	610	50	550	1,100	WL	..	Tapered rollers for turning
			Main work table	4	612	75	550*	550	WL	..	*460 V rating
			Breast rolls	2	610	50	550	1,100	WL	..	
			Screwdowns	2	614	100	485	970	WL	..	

Many of the advantages outlined for the use of static convertor equipment supplying main drives apply also to auxiliaries. The mercury-arc convertor is again the only static conversion device which is suitable for the supply of these drives but the case for replacing m-g sets by mercury-arc convertors is not so clear cut as it is in the case of main drives.

In capital cost the mercury-arc convertor equipment usually shows no saving and often costs more than the equivalent m-g set. Further, the gain in running costs by using mercury-arc convertors is often small.

M-G sets are therefore being used in several cases for the power supply to reversing-mill auxiliaries, even though mercury-arc convertors are

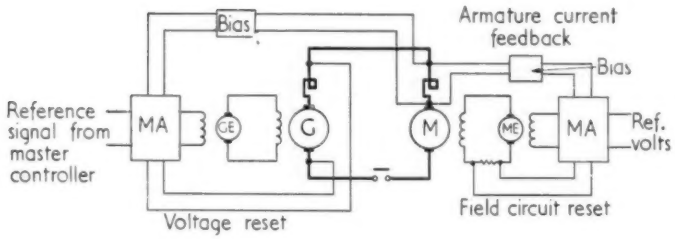


Fig. 2.—Plate-mill main drive, basic control scheme

being used on the main drive. However, there is undoubtedly a very strong attraction to static power conversion equipment. Some reversing-mill auxiliary drives are therefore being installed with mercury-arc conversion equipment, even though the initial cost may be greater. This trend will increase as the costs of static conversion equipments are brought down relative to m-g sets.

CONTROL : MAIN DRIVE

Generator Systems, Rotating Exciters

There are two main requirements of the control systems for a large reversing-mill drive :—

(i) There must be rapid response to the instructions given by the operator so as to give the best degree of control of the rolling operation.

(ii) The control system must enable the drive equipment to meet all the demands made by the operator, up to the maximum capabilities of the equipment, at the same time automatically preventing the equipment from exceeding these maximum conditions independent of any action on the part of the operator.

Fig. 2 shows the basic type of control scheme in use on many plate mills. Separate closed-loop control systems are used for the generator voltage and for the motor field current. These are sequenced to avoid undesirable simultaneous operation. Fast-acting armature current limit control is provided acting on both the generator voltage and the motor field current control system. Both systems are designed to keep the ratio of peak armature current to mean armature current required to achieve a given change in speed, to a minimum. The rates of acceleration and deceleration are adjustable to suit the operation of the particular mill, as are the levels at which the generator and motor current limit circuits come into operation.

Modern control systems of this type can give a rate of response which will reverse the drive from base speed forward to base speed reverse in well under one second. Fig. 3 shows a typical trace of a 5,000 h.p. drive with a base speed of 50 rev/min, in which base speed reversal was obtained in just under 1 sec. Reversal times as low as this are, of course, not often required and the control was adjusted to give slower operation. Once reversal times of $1\frac{1}{2}$ sec. or less are being considered, the

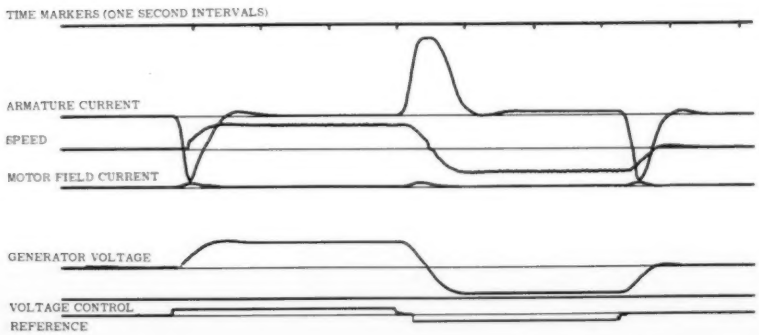


Fig. 3.—Reversal tests, base speed to base speed, on 5,000-h.p. mill drive

important point is not so much the base speed reversal time but the degree of general controlability that the more rapid response gives to the operator.

Motor field system responses can give acceleration times from base speed to top speed of 1½-2 sec. and similar deceleration times. Overall reversal times of between 3 and 4 sec. from top speed are quite normal unless the drive is a high-inertia drive where the limitation is armature current rather than the response of the control system. This total reversal time is somewhat less than the total motor field and generator voltage response times because, although sequenced, the two systems are in fact permitted to overlap to give the maximum overall response.

Generator System, Static Excitation Supplies

The advantages that have been stated for static power supplies for main and auxiliary drives also apply in large measure to static power supplies for excitation. In the basic scheme outlined above, magnetic amplifiers are used for the first stage of amplification but the main excitation power for the generators and motors is provided by a machine. For large reversing mills where excitation powers for the generators will range up to 25 kW and for the motors up to 80 kW, and where field forcing voltages of up to six or eight times normal full excitation voltage are required, the mercury-arc convertor again offers the best static solution. Several large reversing mills using this form of

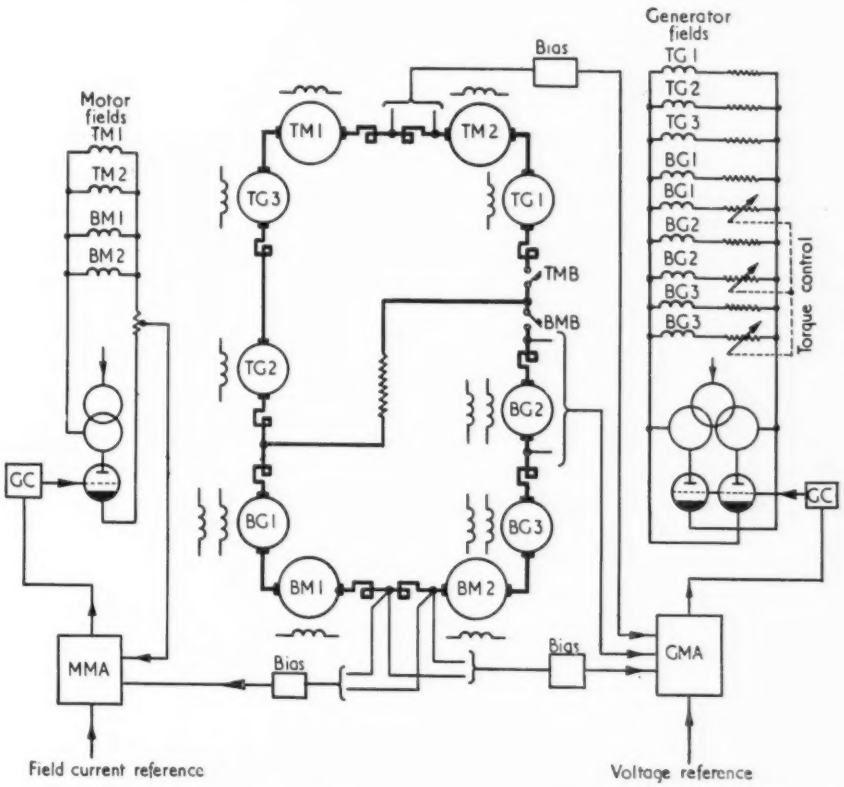


Fig. 4.—Generator-fed twin-drive reversing mill

MMA	Motor magnetic amplifier	TMB	Top motor breaker
GMA	Generator magnetic amplifier	BG1, 2, 3	Bottom generator 1, 2, 3
GC	Grid control	TG1, 2, 3	Top generator 1, 2, 3
BMB	Bottom motor breaker	BM1, 2	Bottom motor 1, 2
TM1, 2	Top motor 1, 2		

excitation are in operation in Europe and several are being installed in the U.K.

Static excitation systems for large reversing-mill equipments may often cost more than the equivalent machine excitation system, even when mercury-arc convertors are used, but in many such cases the extra cost has been considered justified for the advantages gained.

Fig. 4 shows the basic control circuit for a large twin drive in which static excitation using convertors is being adopted for both generators and motors. In this particular case the convertors are capable of providing a field forcing voltage of eight times normal excitation voltage.

Twin Motor Drives

The powers required by modern plate mills are such that in the majority of cases twin motor drives are adopted. In this type of drive the method of speed control is exactly as has been outlined for the single motor drive. There is, however, the additional problem of co-ordinating the control of the two motors driving separate rolls. Two main operational features are required :—

(i) With the roll empty the motors should run at a constant speed proportional to the setting of the operator's control handle and the ratio of the speeds of the two motors should be very closely adjustable.

(ii) Under rolling conditions the two motors should share the load as nearly as possible and should not cause the piece to turn up or down.

Experience has shown that the main factor in the operation of drives affecting the degree of bending of a plate is the relative speeds of the two rolls as the piece enters and while it is being rolled. A speed difference in the two rolls of only a few per cent can have a major effect on the rolling of the plate. The most satisfactory rolling is usually obtained by making the two roll peripheral speeds equal and adjusting the motors to load share as nearly as possible.

Mercury-arc convertor power supply systems

When the mercury-arc convertor is used as the power supply to a reversing drive there is, of course, one overriding factor that affects the whole design of the control system. A single convertor equipment will only conduct current in one direction. A reversing-mill drive must be capable of developing torques in either direction for either direction of rotation.

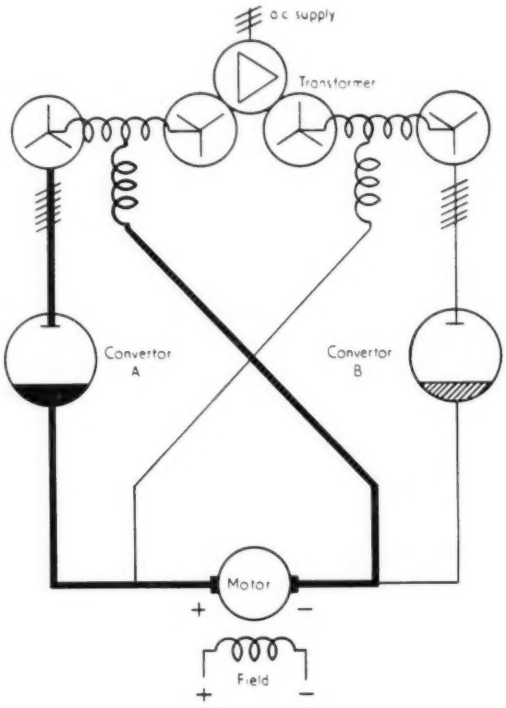


Fig. 5.—Cross connected convertors

This reversing torque can be provided in three ways :—

(i) By arranging two mercury-arc convertor equipments in cross connexion, one conducting in each direction (Fig. 5).

(ii) By providing an armature circuit reversing switch between the motor and convertor (Fig. 6).

(iii) By reversing the motor field and so reversing the torque for a given direction of armature current (Fig. 7).

Each of these systems has been used on reversing plate mills. Their main relative merits are :—

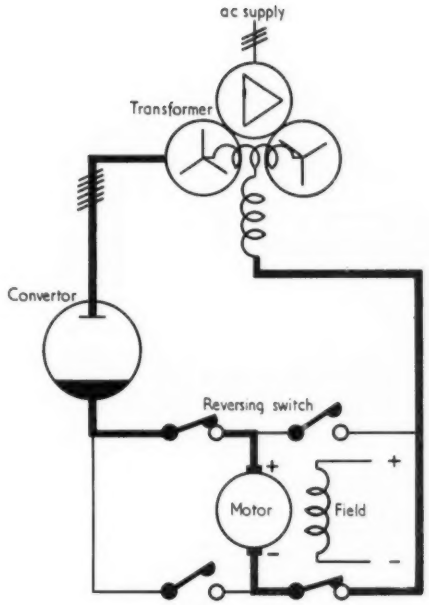


Fig. 6.—Single convertor with armature reversing switch

(i) Cross connexion of convertors as shown in Fig. 5 gives the most satisfactory control but has the disadvantage that it costs more than the other two systems due to the additional convertor equipment required.

(ii) The armature reversing switch scheme employs only one convertor and this is not so costly as the cross-connected arrangement. It requires the use of a large reversing switch and therefore is not so rapid as the cross-connected arrangement because of the dead time for the switch to operate. In some cases it has the advantage over the motor field reversal system of being slightly faster.

(iii) The field reversal system has the same economic advantage as armature reversal of not requiring more than one convertor equipment, and in addition avoids the use of a heavy current reversing switch. It has the disadvantage in some cases that the delay caused by the time taken to reverse the field is slightly longer than the delay which occurs in the reversing switch scheme.

Fig. 8 shows part of the convertor equipment for a 132 in. plate mill to be commissioned this year. The main drive is a twin motor drive with an r.m.s. output of just over 10,000 h.p. at 45-80 rev/min.

CONTROL AUXILIARIES

As already mentioned, in the early plate mills the auxiliaries were driven by a.c. or d.c. motors with simple armature resistance control. This form of control, however, has two big disadvantages when applied to large high-output reversing mills :—

(i) A considerable amount of energy is wasted in the armature resistances, and on a high-output mill the cost of this waste energy when capitalized more than pays for the

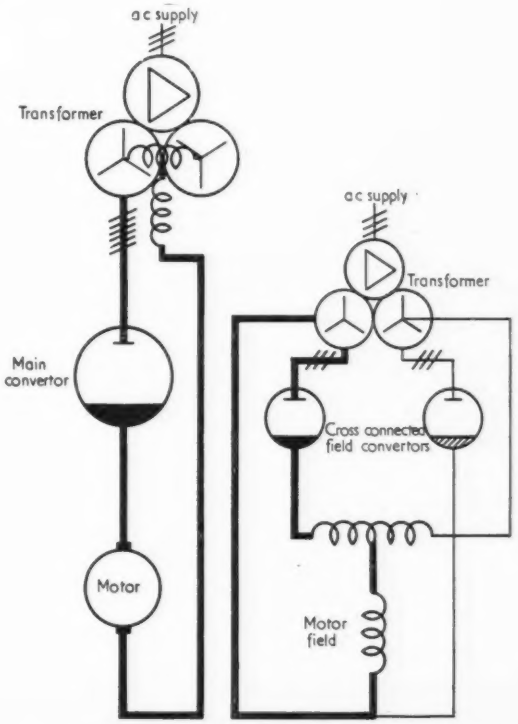


Fig. 7.—Single convertor with motor field-reversing

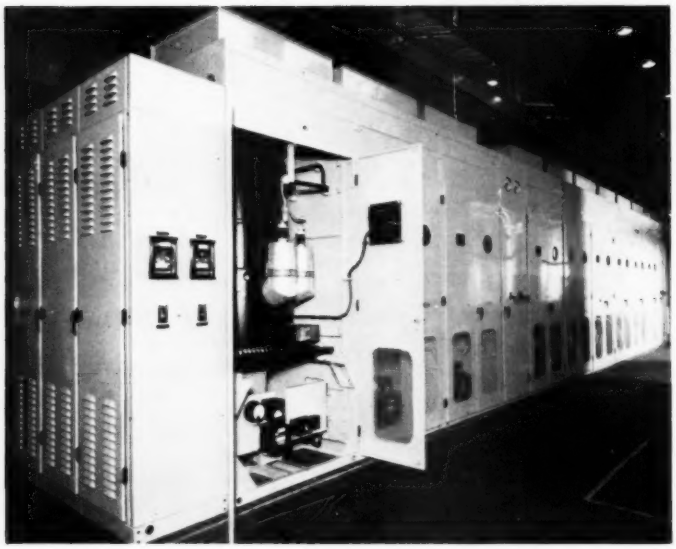


Fig. 8.—Mercury-arc convertor equipment for a plate-mill twin drive

increased cost of a variable voltage supply to each auxiliary drive.

(ii) A modern variable voltage control system can give more rapid response and uses the drive nearer to its maximum capabilities. As the output increases this factor becomes more important, particularly when automatic control is applied to a mill.

The requirements for the control system for the main auxiliaries associated with a reversing mill are the same as those for the main drive. It must give rapid response and it must allow the drives to be used to their maximum capabilities whilst at the same time providing automatic protection.

Fig. 9 shows the basic type of control scheme in use on many modern heavy plate mills. Since the majority of auxiliaries are basically constant torque drives and the peak loads required are those for acceleration and deceleration, all control of speed is done at maximum motor field by varying the generator voltage. Current limit protection is provided to enable the motor to change speed under maximum armature current without danger of excessive overload. A feature of many modern schemes such as this is that no frequently operated contactors or relays are used. The output from the driver's controllers is fed directly into the magnetic amplifier.

Where mercury-arc convertors are used to provide a variable voltage supply to the auxiliary drives, schemes similar to those outlined for the main drive can be used. The two most normally used are either cross-connected convertors or an armature reversing switch. Motor field reversal requires additional equipment for motor field excitation which is not otherwise necessary in the case of auxiliary drives. On the simpler auxiliaries speed control systems are not required and the control is done on the voltage at the motor armature. Where fast control is required, then the cross-connected arrangement is preferable and it is particularly desirable where fast position control systems are required.

AUTOMATIC CONTROL

Up to this point main and auxiliary drives as individual units have been considered, i.e. the motors,

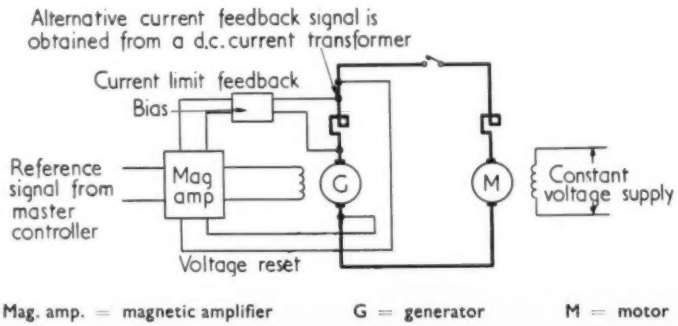


Fig. 9.—Plate mill, Ward-Leonard auxiliary, basic control scheme

their supply, and methods of controlling their speeds. On the first mill, installed at the beginning of the century, the operator's function was to carry out rolling of plate by controlling the speed of the drives. Modern electrical equipment so far considered gives the operator an extremely effective means of controlling the speed for each of the functions concerned in the operation of the mill. The basic function of the operator has, however, been left unchanged in that he still achieves his purpose by controlling only the speed of the various drives. The operation of the mill as a single production unit will now be considered and the extent to which this unit fulfils its purpose in operating in the way so far outlined.

In the discussion that follows, the type of mill borne in mind is the wide four-high heavy plate mill of which several are at present being installed in the U.K. A typical mill would receive slabs 4-10 in thick and 56-108 in wide, weighing from 1 to 7 tons. These would be finished to plates ranging from 60 to 120 in wide and down to $\frac{1}{2}$ in thick. Up to forty-five passes may be involved, which may be rolled in one stand or in two or three stands in succession, each with its own reversing drive.

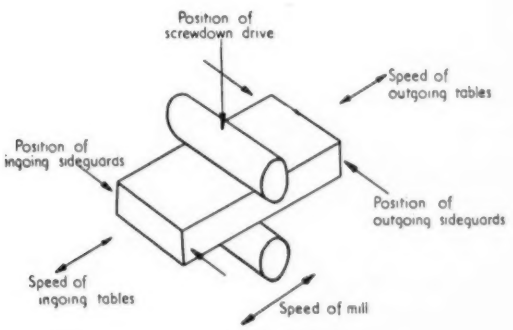


Fig. 10.—*Functions controlled by plate-mill operators*

Fig. 10 shows the functions that have to be controlled by the operators on a typical plate mill with the equipment so far considered. It is the responsibility of the operators to roll the maximum output of plate of the required size, within given tolerances, with minimum stress to the mill equipment. They must do this by the co-ordinated control of the functions shown. The results obtained by the operators using modern systems which control the speeds of various drives are excellent. Nevertheless, marginal losses in the efficiency of operation occur for a number of reasons :—

(i) Operators are unable accurately and consistently to move the screwdowns through small distances without loss of time owing to the need to 'jog' the drive to overcome stiction.

(ii) It is not possible to utilize efficiently the maximum capacity of the various drives, in particular the main and screwdown drives.

(iii) There is loss of concentration of the operators. This can result in either lost time and errors in co-ordination of the various drives forming the production unit or inconsistent rolling procedure, which can in turn affect the consistency of the product leaving the mill.

(iv) Delays occur when measuring thickness and width of plate.

(v) There can be errors of calculation which prevent rolling from being carried out efficiently in the minimum number of passes. For example, it is necessary for operators to determine the draft to be taken to roll a required length of plate in the minimum number of passes. It is also necessary for an operator to estimate the most efficient draft settings, to be taken on the final passes, to obtain a plate thickness within the required tolerances.

When reviewing the development of systems to control the speed of main and auxiliary drives it was pointed out that fast responses and inherent protection were obtained by adopting the principles of feedback control, in other words, removing from the operator the responsibility of watching how a drive performs the task required of it and including this responsibility within the control system. In the same way the effect of various factors leading to loss of operational efficiency can be reduced by taking more control functions from the operator and including them within the control

system. Reorganisation of these functions can be divided into four main aspects. Logically the first is to replace the control of speed with a control of position, where it is position that matters, not speed : this applies to screwdowns and sideguards. The next is to provide automatic sequencing control which will accurately and consistently perform the operations of slowing down and stopping the mill and initiating the movement of screwdowns and sideguards. The third is the storage of information required to roll a particular piece, so that the operator need then only refer his control functions to this information store. Such 'program control' provides consistent operation and thus a consistent product. In conjunction with automatic positioning and sequencing control a completely automatic mill can be obtained provided that all operations can be accurately determined beforehand. Since this is not always possible it is desirable, as the fourth main aspect of reorganisation, to feed back, from the quality of the product, signals to modify the operation of the control system to produce the desired finished product. To achieve this the first essential is a means of measuring those qualities which are a function of the operation of the mill ; the second is to interpret results obtained from such measurements and decide what modification should be made to the controls : for this a form of computer is necessary. In the rest of this paper these aspects of the logical development in the control of plate mills are considered to emphasise their more important operational features.

Position Control Systems

Screwdown

Of the various functions shown in Fig. 10, the screwdown drive is the obvious one to study first. It is this function that the operator has to control in every interval between passes, so that even if he takes only a fraction of a second too long at each adjustment a significant reduction in output can result. Fig. 11 shows, in full line, the ideal form of the speed/time relationship and speed/position relationship when moving the screwdowns a comparatively large distance. The acceleration and deceleration rate should be a maximum, as dictated by the torque capacity of the screwdown motor. Although it is comparatively easy for an

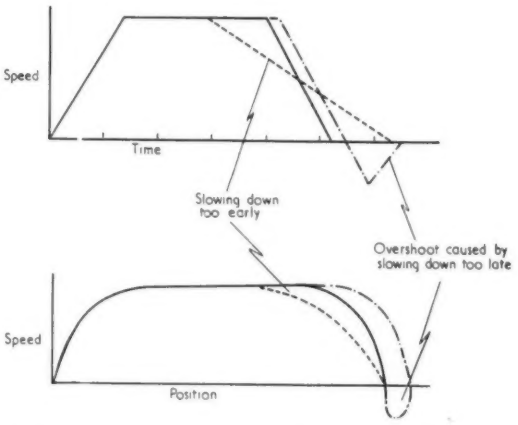


Fig. 11.—Ideal form for speed/time and speed/position characteristics for a screwdown drive

operator to ensure that maximum use is made of the torque capacity to accelerate, it is not so easy for him to determine the exact point at which deceleration should begin. If he decelerates too soon, as indicated by the dotted line in Fig. 11, he will not make full use of the available torque. If he decelerates too late he will overshoot the desired position. In either case time will be lost in positioning the screwdowns.

When making small movements the effects of stiction and friction in the screwdown mechanism can prevent the operator from responding with sufficient speed to ensure accurate positioning without overshoot. To obtain small and accurate screwdown movements the operator desires the drive to accelerate and decelerate at a comparatively low and controllable rate, as shown in Fig. 12(*a*). The effect of stiction, shown in Fig. 12(*b*), demands that the motor current rise to a comparatively high value (Fig. 12(*c*)) before the drive can move. As soon as the drive starts to move, the stiction force is replaced by the lower friction value and the excess motor current causes the drive to accelerate at a higher rate than that desired by the operator (Fig. 12(*a*)). To avoid this effect, which can result in an overshoot of the desired position, an equally inefficient yet more precise method of control is resorted to. This is a method of jogging or bumping the drive in small movements towards the desired position.

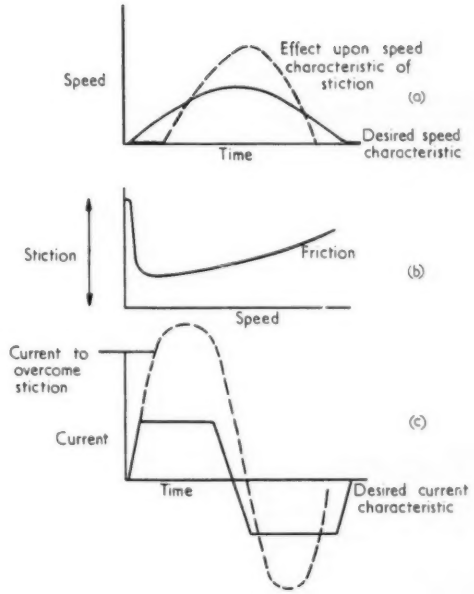


Fig. 12.—Effects of stiction on a screwdown drive

The position control systems now available overcome these problems and enable screwdowns to be accurately positioned in a minimum time. The use of a fast and accurate position control system also has two other advantages. First, it relieves the operator of having to drive the screwdowns during the interval between passes, so that he may concentrate on other functions. Second, it makes it much easier to position the screwdowns accurately and therefore results in a greater consistency of product. Where a preset control can be provided this advantage is further enhanced.

There are many different types of position control system which will meet all the requirements of accuracy and speed of response of plate-mill screwdowns. These may differ in the method used to detect position, i.e. synchros, potentiometers, or digital means, and in the form of amplifier used in the feedback control system. Whatever the type of system used, however, there are certain fundamental features common to them all which must be considered in their design and application.

In essence, a position control consists of a normal manual control system embraced by a closed-loop position control, as shown in Fig. 13. The position control loop consists of a means of inserting a signal proportional to a desired position and a means for measuring and comparing the actual position of the screwdown with the desired position. The difference between these signals is amplified and used to drive the system to the desired position.

It is essential, for both the designer of a position control and the user, to be able to define clearly the performance requirements of the screwdown position control. The most suitable way of doing this is to consider the performance under two headings ; ' steady-state accuracy ' and ' transient performance '.

Steady-state accuracy

The performance of a screwdown position control is affected both by the characteristics of the screwdown gear to which the control system is applied, and by the characteristics of the closed-loop control. It is desirable to take this into account when assessing the accuracy of a system, by making use of three terms ; first, the steady-state accuracy as an assessment of the ability of the overall system to position the screwdown roll at any desired position ; second, repeatability or consistency, to assess the ability of the system to roll plate accurately on the finishing passes when small trimming movements of the screwdown roll

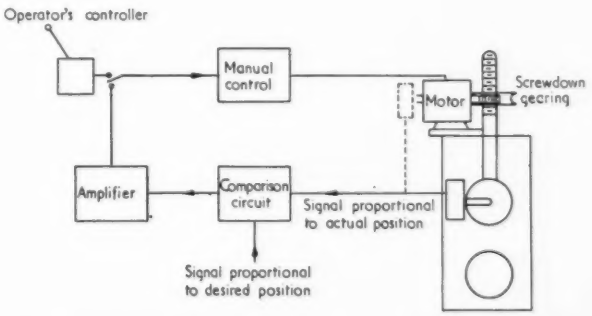


Fig. 13.—Closed-loop position control applied to a screwdown drive

are required, and third, control system accuracy to assess the sensitivity of the closed-loop control both as a basis for designing the closed-loop control and as a common basis for comparing several systems.

Steady-state accuracy of a screwdown position control may be defined as the error to be expected between the actual position of the screwdown roll and the desired position. This figure takes into account all effects, both within the closed-loop control and within the screwdown mechanism, which would give rise to an error in position.

Repeatability or consistency of a screwdown position control may be defined as the error to be expected if an attempt is made either to repeat a given draft or to position repeatedly at the same position. This figure gives an assessment of the minimum tolerance, in plate thickness, which it is possible to roll and the consistency obtainable in finished product.

Control system accuracy may be defined as the smallest error in the position of the measuring device which the control system will attempt to correct when the system is stationary. The significance of this definition is that, for a given stiction effect, the control system accuracy is only dependent upon factors within the closed loop of control. It provides a direct measure of the sensitivity of the control system and forms a criterion for design.

The control system accuracy is a function of control system amplification or gain. The higher the amplification in the system the smaller is the error in position required to provide sufficient torque to overcome stiction in the drive. This applies equally to continuous control systems, such as those employing magnetic or electronic amplifiers, and to discontinuous control systems using relays and contactors in cascade to amplify the error signal. However, in practice the dead zone effect of a discontinuous control system can put such systems at a disadvantage when compared with continuous control systems having no dead zone effects. This dead zone effect is the main reason for preference being shown to continuous control systems, for plate-mill screwdowns, where optimum repeatability and steady-state accuracy are essential.

For this optimum in performance it is desirable to obtain as high a control system accuracy as possible. However, a high system gain included in a system to achieve this can cause instability in either of two ways. First, an instability or hunting caused by the limited resolution of the measuring device which can cause the system to hunt between two discrete positions on either side of a desired position on the measuring device. Second, hunting caused by backlash within the closed loop of control. While it is possible to obtain measuring devices of high resolution, or in effect infinite resolution, the problem of backlash instability is more difficult to overcome. Attaching the measuring device to the screwdown roll, to measure its position accurately, has the disadvantage that the backlash of the screwdown mechanism is included within the closed loop of control. An alternative arrangement to avoid this (dotted line in Fig. 13), is to attach the measuring device to the screwdown motor and to eliminate all backlash from within the closed loop. This allows a high system gain to be used to provide a high control system accuracy. The backlash in the screwdown gear outside the closed loop can then be taken up consistently in one direction by arranging the transient response of the system to be slightly different for the two motions of screwdown movement.

Transient performance

The transient behaviour of the screwdown should be considered under two conditions. First, when making the smallest screwdown movement normally required, and second, when making movements which would be expected to take the motor to full speed.

When making a small movement, not only is it necessary to overcome the force of stiction in the drive, but it is also necessary for the drive to brake quickly and accurately at the desired position. The system must respond rapidly to avoid the same difficulties experienced by the operator in controlling the high rate of acceleration when stiction is overcome.

When making larger movements, to position in a minimum time, it is essential to utilize the full available torque of the driving motor to accelerate and decelerate so that the drive runs at full speed

for as long as possible. This desired characteristic is shown in full line in Fig. 11. A low system gain will cause the drive to decelerate when the error in position is still comparatively large and will prevent utilisation of maximum torque. Although a high system gain avoids this, if the gain is sufficiently high it is possible to hold the screwdown motor at full speed for too long and to overshoot the position because the operation of torque limiting circuits built into the system prevents excessive rates of deceleration. It is desirable to obtain an approach characteristic, plotted between speed and position, similar to that shown in full line in Fig. 11, without having to limit the control system accuracy. This may be done by using circuit elements in the system which shape the approach characteristic and in effect limit the system amplification when the drive is running at speed. In practice such circuit elements can be adjusted to give the desired approach characteristic and still allow a high system amplification to be used for small movements of the screwdowns.

Optimising performance of position controls

To obtain optimum performance, both in response and accuracy, a high system gain or system sensitivity is essential. A limit to high gain can be caused by dead zone effects, limited resolution of the measuring device, or backlash within the system. These must be avoided or reduced. Special consideration must also be given to ensure that movements can be made without excessive overshoot caused by either stiction or torque limitations of the system.

Method of operating a position control

With the application of a position control to a screwdown the method of operator control is of particular concern. If controlled directly by the operator the controls must at least be as simple to use as the speed control previously used by the operator. It is desirable that a setting for a following pass can be made while the work-piece is being rolled and that the actual screwdown movement is initiated by the operator when required. It is also desirable that settings should be made by touch without it being necessary for the operator to take his eyes from the mill.

There are two basic methods for calibrating the operator's controls ; first, a control calibrated in terms of the roll gap setting, and second, a control calibrated in terms of draft of screwdown movement to be made on each pass. While either method of control can be applied to a plate mill, draft control is of particular interest. It provides in a simple control a means of easily setting the extremely small movements normally associated with finishing plate mills. It also provides controls directly calibrated in terms of the corrections given to the screwdown operator when the piece is gauged for size.

Sideguards

The required action of the sideguards control is one which allows the operator to move the sideguards to any desired position across the mill tables. Therefore all that has been said of a screwdown position control broadly applies to sideguard position controls. The most significant difference between the control of sideguards and the control of screwdowns is in the method by which the operator controls them. The most simple form of sideguards control is that using a control, such as a lever, to control the distance between the two sideguard heads rather than individual controls for each sideguard. This method can be extended to take advantage of the fact that on a plate mill, as opposed to a primary reversing mill, only a limited number of positions are required for rolling several passes. On a typical mill there are two control levers, one to set the sideguard position for guiding the plate into the mill and the other to set the sideguards to a wider position for receiving the plate as it leaves the mill.

Pre-set control

Often the positions required for sideguards and screwdowns for each pass in a program can be determined beforehand, particularly on roughing and intermediate plate-mills. If in such cases the control can be pre-set to store this advance information, then obviously a significant advantage is gained. The operator's job is made easier since now he has only to initiate the action of the auxiliaries concerned for each pass. Since each example of a given program will be rolled to exactly the same pre-set information, consistency is ensured. A set of rheostats, one for each pass, forms an elementary method for carrying this out.

An alternative is to use a plugboard to select, by means of plugs, the required screwdown and sideguard positions to roll a given product.

It is obvious that this technique of pre-selection can be extended to embrace the remaining control functions on the mill complex shown in Fig. 10. These are the mill and table speed settings associated with each pass rolled.

Sequencing

If the settings for speeds and positions of the various functions of a mill equipment are pre-set for all passes in a program, then the operator's job is greatly simplified. He has now only to supervise generally the operation of the mill and to initiate in the correct order or sequence the action of the various functions in accordance with the pre-set information. As has already been suggested, in carrying out this function the operator can fall short of optimum performance by loss of concentration. To avoid this, and to maintain a high operational efficiency, this function can be carried out for the operator automatically. The method of control is shown in Fig. 14. The nose and tail of the work-piece can be detected by infra-red cells which feed information to a logic unit. Also fed to this unit are electrical signals from the various drives indicating whether or not a particular drive is in motion. From these signals the correct operation of the control functions is determined and the sequence of operations controlled.

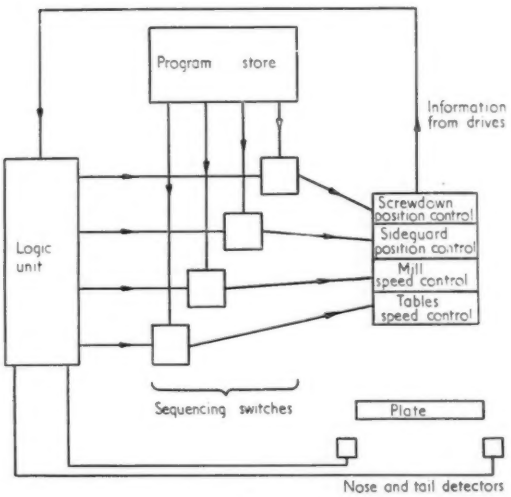


Fig. 14.—*Automatic sequencing of programmed information*

With the introduction of such a unit to eliminate an important control function of the operator, it is necessary to evaluate the new role of the operator and determine the essential control that he must still maintain over the mill complex.

The operator now has an automatic mill or, in effect, an elementary robot which faithfully carries out instructions which have been given to it. From signals received from the drive and work-piece detectors it is able to carry out simple logical processes. However, if unforeseen factors upset the normal sequence it is imperative for the operator to be able to intervene at once. There are four methods by which an operator may wish to supervise :—

(i) By freezing the whole program, as he may wish to do when the plate is required to be checked for dimensions.

(ii) By modifying the program for any one control, without affecting other parts of the program. An example of this would be to bias the position of the sideguards to assist the entry of a piece into the mill, or to bias the screwdown position to account for roll wear.

(iii) By cancelling the program to one function but carrying on with the program of control of other functions, e.g. manual setting of the screwdowns to control the gauge of plate on finishing passes.

(iv) By cancelling an entire program so that complete control may be returned to the operator.

All four methods of operator supervision will normally be required, arranged in such a manner that the desired degree of supervision can be obtained by the operator easily and quickly. This is of the greatest importance in ensuring that the system has optimum flexibility.

Program Control

Having established the use to which a storage system for the storage of one rolling program

may be put, it is apparent that the storage of more than one rolling program would also have advantages. With such a storage system the operator can call for any one of a large number of programs all of which would have been perfected on previous occasions.

The form of storage system chosen for a given application depends upon the number and size of programs, the time available to find a program, and the complexity and reliability of equipment.

There are four basic methods used for such systems :—

(i) Relay systems.
(ii) Punched card or punched tape systems.
(iii) Magnetic storage systems.
(iv) Electronic storage systems.

Examples of all four systems are in use either in the steel industry or in applications outside the steel industry.

Relay systems

A relay system can be characterised as one which provides a comparatively cheap and permanent store, of limited capacity, yet one which provides speedy access to information. Of particular interest are systems utilising the uniselector relay, an example of which is the translator system developed by BISRA. The information is stored by wiring, on to a matrix of terminals, connexions corresponding to the various settings on the mill. The operator selects a program on switches calibrated in terms of the rolling parameters, such as ingoing and outgoing piece dimensions. In so doing, he causes uniselector relays to select the required program of terminals to roll that product. The technique used to find the programs is very similar to the techniques used in automatic telephone exchanges. Fig. 15 shows a storage equipment, based upon uniselector relays, capable of storing the information for two position controls and one speed control and for sequencing this information. The particular equipment shown is capable of storing fifty programs with fifteen passes per program.

Punched card or tape

Information may be stored on punched cards or punched tape by forming a pattern of holes

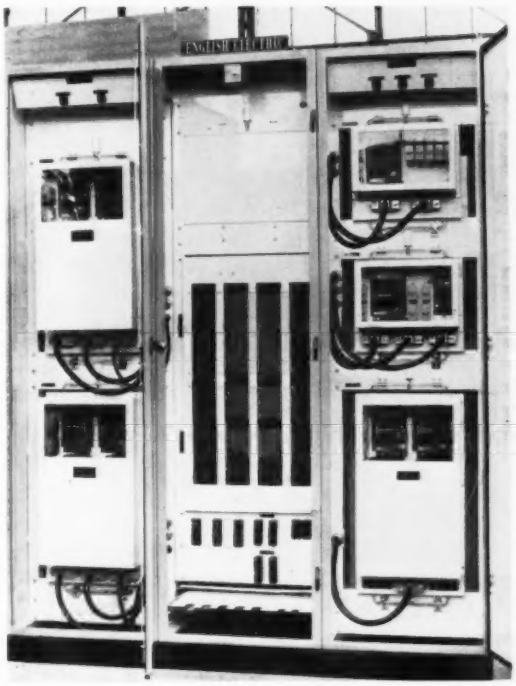


Fig. 15.—Uniselector storage and sequencing equipment for two position controls and one speed control

that can be read either by mechanical sensors or by photo-electric detectors. Fig. 16 shows a type of punched card used widely in standard business data and computer applications, and next to it a punched tape used for recording teleprinter messages. Systems using punched card or tape are possibly the most flexible available for storing rolling-mill programs but can, if speedy access is required from a large store, be complicated by needing auxiliary sorting equipment. To appreciate fully the characteristics of the various systems which have been developed, it is desirable to sub-divide further the punched card and punched tape systems.

Business card systems—These systems utilise equipments developed for handling business office data. Use is made of standard business card readers and standard business card sorters. A number of systems in operation utilise several cards to store the information for one rolling

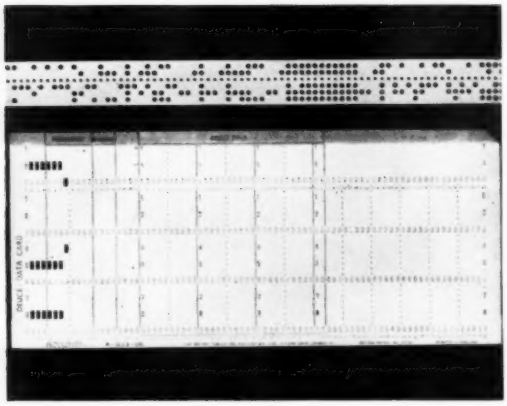


Fig. 16.—Information storage on punched card and punched tape

program. These cards are read in rapid succession in a standard business card reader which transfers the information into a buffer store. It is retained here, for as long as it is required, and is available for controlling the mill pass-by-pass.

Special card systems—To overcome the necessity of a buffer store, which can be a comparatively complex system, it is advantageous to utilise a card reader which allows the card to be read pass-by-pass, either on a matrix of hole detectors or by moving the card over single or double rows of hole detectors. However, the information to be stored for a single rolling program is often too much for one business card. To avoid the necessity of having to use several cards, one system uses a special card (shown with its card reader in Fig. 17) which can be extended in length to accommodate all the information required for a single program. In applications requiring only a limited number of programs, the use of single cards can avoid the necessity of special card sorting equipment. To prevent damage to cards through constant handling, this system uses cards made of a more durable material than is normally used for standard business cards.

Punched tape—Punched tape systems have been developed which are very similar to the card systems. However, with these systems some form of automatic sorting and tape handling is necessary. One such system utilises a reel of tape containing several programs. The operator, by selecting his program on switches in much the same manner as with the uniselector system, causes the tape to be read at high speed to find the starting point of the program. The tape is then stopped and read pass-by-pass to control the mill.

Magnetic and electronic methods

Magnetic or electronic methods for storing information are used widely in computer systems where their main requirements are maximum storage in the minimum space, high speed of access,

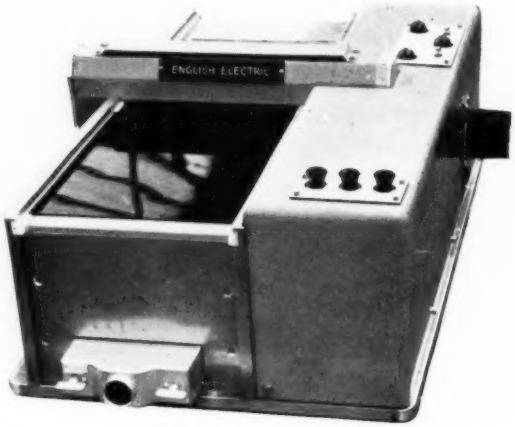


Fig. 17.—Special card reader developed for storing rolling-mill program data

and ability to retain or change the information quickly. To obtain these advantages the equipments are more complicated and costly than the systems already described. As yet, the requirements for storing rolling-mill programs have not warranted the extra complexity of such equipments. However, their advantages may well be necessary in future applications of automatic techniques, particularly in the application of techniques of data handling and production control.

Measurements

The most recent developments of automatic control techniques for plate mills have been concerned with the development of suitable

measuring devices. The intention is to provide equipment to measure accurately and quickly the length or width of plate and its thickness, so that this information may be presented in a suitable form to the operators. For plate width and length measurements where accuracy of measurement depends upon the accuracy of plate edge detection, photo-electric methods of detection appear to be the most promising. Several measuring units using this form of detection have been developed ; one, for instance, is a method of mechanically traversing the plate with a photo-electric detector head and counting the number of electrical pulses supplied from the mechanism when moving from one edge of the plate to the other. For plate thickness measurement, methods utilising X or γ rays have proved successful for the thinner gauges. But for thicker plates, the dangers to operators, inherent in powerful radiation sources, prohibit their use. A method of automatically calipering the plate with mechanical feelers appears to be most promising.

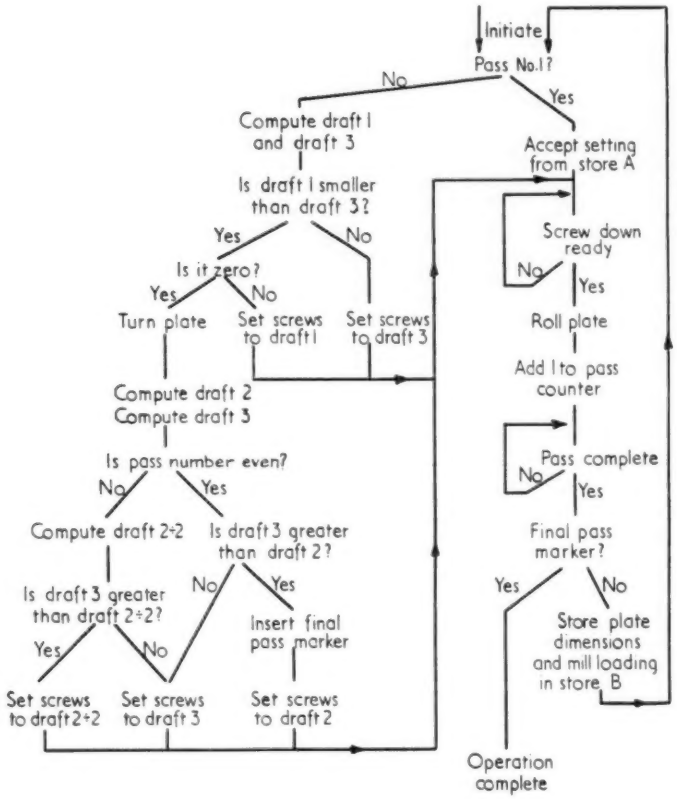
Although, as previously mentioned, it is first necessary to be able to present in a suitable form the measurements of the plate to the operator, the second step is to be able to feed these measurements to a suitable computer. Such a computer could then carry out calculations to assist the operator in optimising his program to obtain, in the minimum number of passes, plates of the required dimensions.

Computer Techniques

It has been shown in practice that, by applying position controls to the screwdowns and sideguards and using a program store, the operator can be relieved of many of the routine functions of rolling a given work-piece. In so doing, these functions can be carried out at least as fast and as accurately as the operator and often more consistently throughout a long shift. However, the operator is still being called upon to take over control, either entirely or partially, when a desired rolling program cannot be decided beforehand. For example, on many mills producing close-tolerance plates it is unlikely that a program can be relied upon accurately to roll a plate to a length which, on turning, becomes the required accurate plate width. Even if this were possible it is unlikely that by programing the screwdowns to a given roll gap the plate will be accurately finished to the required thickness. The reason for returning to manual control is the failure of the program to take into account the many factors such as temperature of work-piece and mill spring which affect the finished dimensions for a given roll setting. Automatic means for measuring the dimensions of the piece and presenting this information to the operators will greatly speed up rolling by avoiding the necessity of stopping to take measurements manually. However, operator control will still not give rise to maximum operational efficiency, as no assistance is being given to the operator to interpret these measurements. Reliance is being placed upon the judgment of the operator not only to obtain the required plate dimensions but also to ensure that the plate is rolled in the minimum number of passes and therefore the minimum time.

Computer techniques are already being used to overcome similar problems in the steel industry. A typical example is the computation of the most economical lengths in which to cut a rolled section, from a knowledge of the rolled length and a stored knowledge of the order book. This problem has resulted in the design of a special computer, far simpler, faster, and more reliable than the larger and more expensive general purpose computer from which its development stemmed.

Although the application of computer techniques to plate mills is somewhat in the future, the possible course of evolution can be illustrated. In the first instance when rolling a plate for a length which on turning becomes the desired plate width, a computer could be used which can calculate, from a knowledge of the elongation of plate for a given draft, the total draft required to give the desired plate length by assuming a simple proportionality between elongation and draft. When rolling automatically, from settings obtained from a stored program, such a computer would provide the operators with an indication of the most suitable point at which manual screwdown settings should be taken over from the program. Also, an estimate would be available of the most suitable draft to be taken to obtain the final plate length.



Draft 1 = draft to give required elongation
Draft 2 = draft to give required thickness
Draft 3 = maximum permitted draft
Store A = screwdown setting for pass 1
Store B = Results of rolling

Fig. 18.—Sequence of computer operation

With such a method, the answers obtained by the computer after each pass would be slightly incorrect due to various mill effects. The fact that after each pass the answer would be nearer to the right one can be used as a further stage in developing the computer technique. By allowing the computer to observe that after each pass its previous evaluation was incorrect, it can be arranged to weight its answers and reduce the error after each pass. At this stage the necessity for the operator to decide when to take over can be avoided by allowing the computer to insert the last draft as soon as the estimated draft is within the capabilities of the mill, this being decided by the computer from measurements taken of mill loading and draft.

Rolling on the final passes to give a required thickness of plate can be calculated and controlled by the computer in much the same way as suggested when rolling for length of plate. However, it becomes apparent that the use of a computer to take over from a program store to roll the final passes can be extended to replace the program store almost entirely. The extra requirements for computer control are that rolling shall be carried out in the minimum of passes and that this number shall be odd, so that the piece finishes on the outgoing side of the mill. The computer operation illustrated in Fig. 18 would then be :—

(i) The computer has fed to it the actual ingoing dimensions and the required dimensions of the plate.

(ii) The program store provides the first screwdown setting, which is then rolled.

(iii) From measurements taken on this pass, the computer now has three calculations to make : (*a*) the draft required to give the total elongation ; (*b*) the draft required to give the finished plate thickness ; (*c*) the maximum draft permitted. This can be calculated from a knowledge of the loading of the mill and the draft taken on the first pass. The smaller of these draft settings is then used for pass two.

(iv) Rolling proceeds until the draft for giving the desired elongation is the smaller, and when this pass is rolled the plate is turned.

(v) The computer need now only consider the maximum allowable draft and the total draft required to give the desired plate

thickness. However, the further requirement of finishing the plate on the outgoing side of the mill must also be considered. A simple way of doing this is to divide by two the answer arrived at for the total draft to give the final plate thickness, whenever the plate is on the outgoing side of the mill. When this figure is less than the maximum allowable draft, only two passes are required at this setting to finish the plate on the outgoing side.

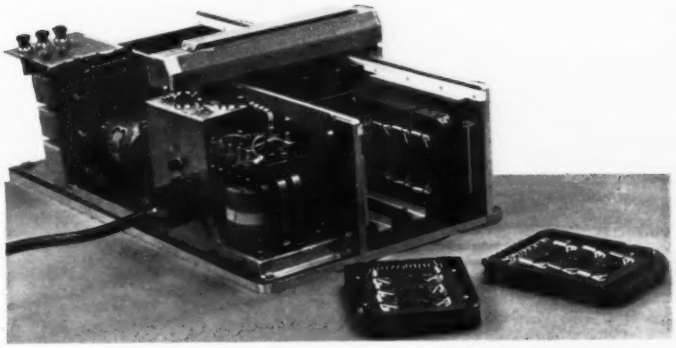


Fig. 19.—Plug-in blocks of components for card reader, facilitating quick replacement of faulty component

Before such computer techniques can be applied to a particular mill, an extensive study must be made involving the equipment manufacturer and the user.

Reliability

Development of automatic control systems has been greatly affected by the question of reliability. In adapting techniques from other fields of application, efforts have been made to simplify the systems and to utilise reliable and well tried components. However, additional equipment such as storage equipment, no matter how reliable, obviously increases the possibility of faults occurring. To counteract this and to make such equipments acceptable in the steel industry, fault location techniques have been built into many of the systems mentioned. These techniques can be summarised as techniques of systematic and simple fault detection location, and component replacement.

One of these techniques is used on a special card reader (Fig. 17). In preparing the cards an extra space is made available for each pass. A hole is then punched, as required, to make the total number of holes for any one pass an odd number. Should an even number of holes be detected during rolling, a fault must have occurred and the system will freeze the mill and thus fail to safety. A special card can then be fitted into the card reader which systematically checks each hole detecting circuit to indicate the faulty one. By using plug-in techniques for blocks of components (as shown in Fig. 19) the faulty unit can be quickly replaced.

THE BASIC AIM OF ALL TECHNICAL DEVELOPMENT is to evolve systems which will give a higher quality product, which will have a lower capital cost for a given performance, and which will cost less to run and maintain. Plate-mill electrical equipment is no exception to this and each of the developments outlined in this review has contributed to one or more of these aims. Future development work will have the same purpose, and the scope is wide.

Two main trends are clear : the increased use of static devices for power supply and for control, and a continued increase in the scope of control systems and information handling systems to aid the human operator by carrying out, on his behalf, more and more of his controlling functions. These two trends will characterise the development of electrical equipment for plate mills over the next decade.

Static devices will continue to replace moving components, including relays and switches as well as machines. This, together with the use of improved fault-finding techniques and plug-in unit assemblies will reduce shut-down time in spite of more complex circuits.

Extension of the coverage of control systems will first be to the automatic control of a single mill unit. It will, however, rapidly extend beyond that

to the co-ordination of several mill units in a production line and integration of the control of mills with the processes before and after the mills. This field of development will have one very important aspect : the co-ordination of several engineering and administrative activities, which so far it has been possible to allow to proceed separately to a very large extent. In future there will be an increasing need to carry out the mechanical and electrical engineering and the production planning as a single co-ordinated operation. Only by the close co-operation of manufacturer and user, designer and operator, will the full benefits that control system development offers be obtained.

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REFERENCES

[1] *R. B. Sims* : *Proc. IME*, 1954, 168, 191-200.

[2] *P. M. Cook* and *A. W. McCrum* : ' The calculation of load and torque in hot flat rolling ', 1958, London, British Iron and Steel Research Association.

[3] *J. H. Taylor* : ' Iron and steel engineer yearbook ', 1956, 823.

[4] *E. C. Larke* : ' The rolling of strip, sheet and plate', 1954, London, Chapman and Hall.

[5] *NEMA* Standard MGI-1959, Part 13.

[6] Direct-current mill motor standards, AISE Standard No. 1, 1957, ' Iron and steel yearbook ', 1957, 941.

[7] *D. Selby Bigge* : *JISI*, 1907, (I) 63-87.

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